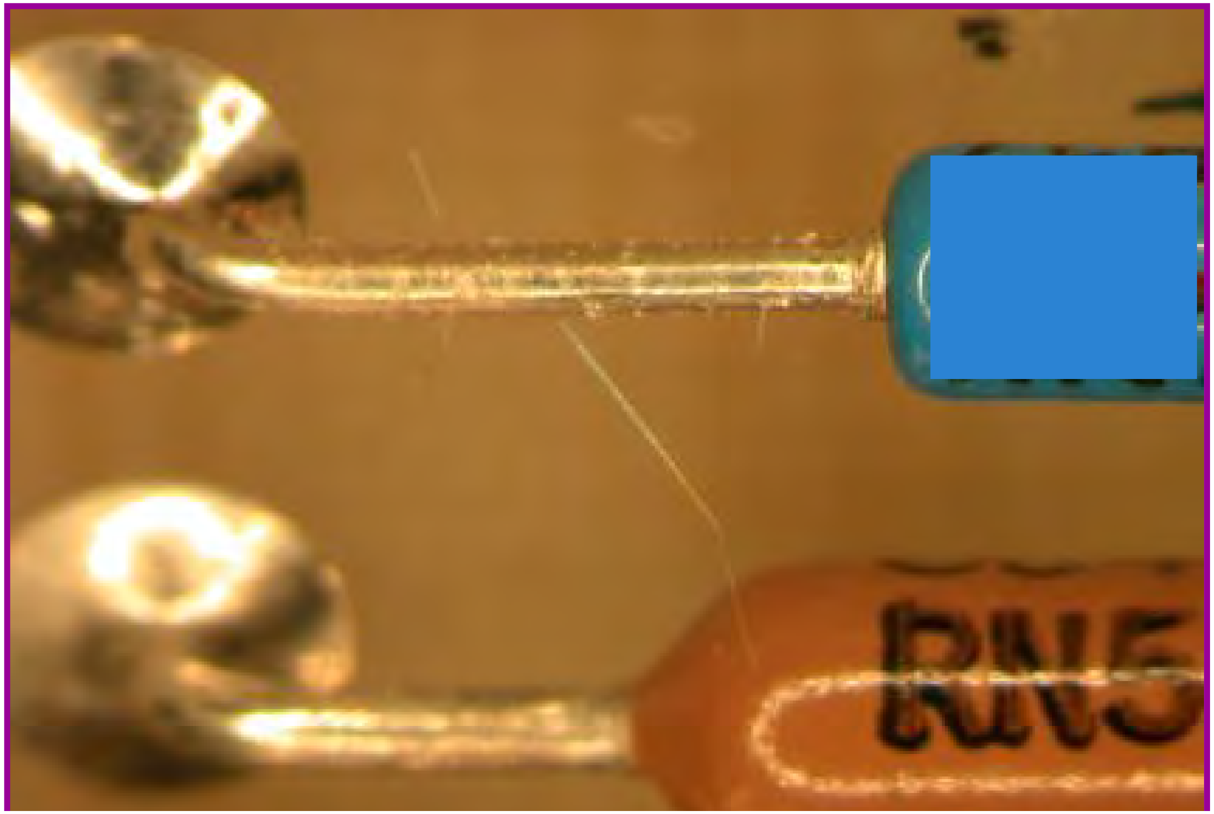
Metal Whiskers

A Discussion of Risks and Mitigation



Jay Brusse / Dell Perot Systems

Dr. Henning Leidecker / NASA Goddard

Lyudmyla Panashchenko / NASA Goddard

http://nepp.nasa.gov/whisker

November 30, 2010

2010 Environmental Technology
Technical Symposium and Workshop

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 NOV 2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Metal Whiskers: A Discussion of Risks and Mitigation**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Dell Perot Systems at NASA Goddard Space Flight Center,Building 22 Room 011 (Code 562),Greenbelt,MD,20771**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 15th Annual Partners in Environmental Technology Technical Symposium & Workshop, 30 Nov ? 2 Dec 2010, Washington, DC. Sponsored by SERDP and ESTCP.

14. ABSTRACT
Metal coatings, especially of tin, zinc and cadmium, are unpredictably susceptible to the formation of electrically conductive, crystalline filaments referred to as metal whiskers. The use of such coatings in and around electrical systems presents a risk of electrical shorting. Examples of metal whisker formation are shown with discussion of optical inspection techniques to improve probability of detection. The failure modes (i.e., electrical shorting behavior) associated with metal whiskers are described. Based on a 10 plus year study, the benefits of polyurethane conformal coat (namely, Arathane 5750) to protect electrical conductors from whisker-induced short circuit anomalies is discussed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**49**	

METAL WHISKERS: A DISCUSSION OF RISKS AND MITIGATION

MR. JAY BRUSSE
Dell Perot Systems at NASA Goddard Space Flight Center
Building 22 Room 011 (Code 562)
Greenbelt, MD 20771
(301) 286-2019
Jay.A.Brusse@nasa.gov

CO-PERFORMERS: Dr. Henning Leidecker and Ms. Lyudmyla Panashchenko
(NASA Goddard)

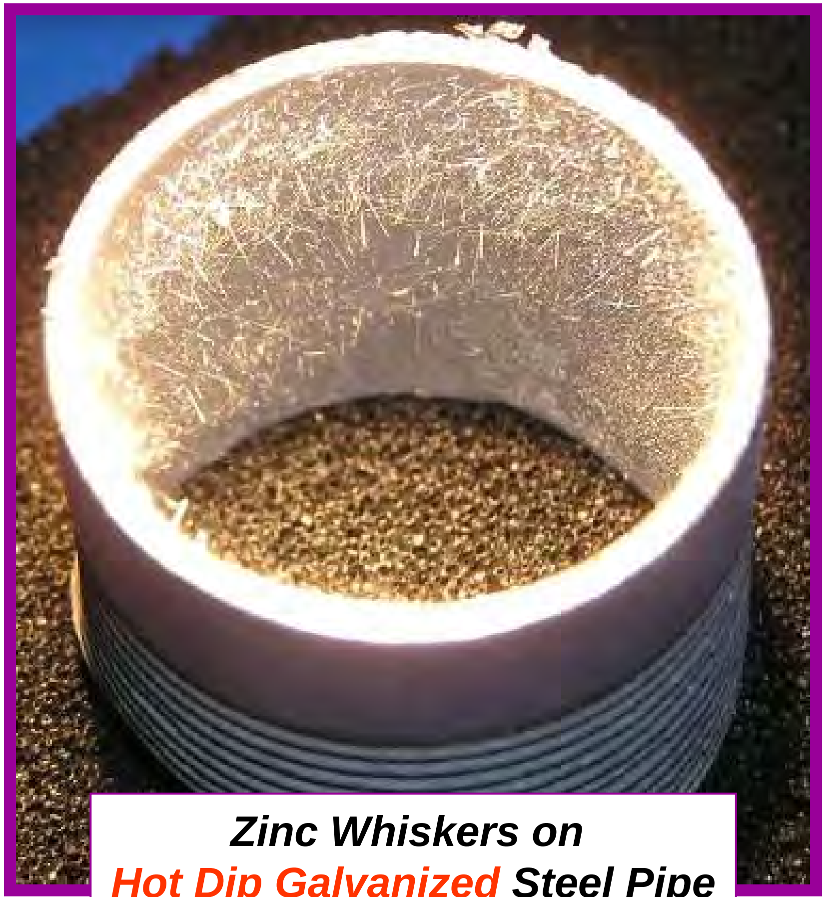
Metal coatings, especially of tin, zinc and cadmium, are unpredictably susceptible to the formation of electrically conductive, crystalline filaments referred to as metal whiskers. The use of such coatings in and around electrical systems presents a risk of electrical shorting. Examples of metal whisker formation are shown with discussion of optical inspection techniques to improve probability of detection. The failure modes (i.e., electrical shorting behavior) associated with metal whiskers are described. Based on a 10 plus year study, the benefits of polyurethane conformal coat (namely, Arathane 5750) to protect electrical conductors from whisker-induced short circuit anomalies is discussed.

Outline

- A Brief History of Metal Whiskers
  No Growth Theory
  To Be Discussed!!!

- Electrical Properties of Metal Whiskers
  Character of Short Circuits

- NASA Whisker Mitigation Study
  Arathane 5750 Conformal Coat



Zinc Whiskers on
Hot Dip Galvanized Steel Pipe

Cover Photo:
Tin whiskers on Tin-Plated Diode Terminals (Courtesy Ted Riccio - STPNOC)

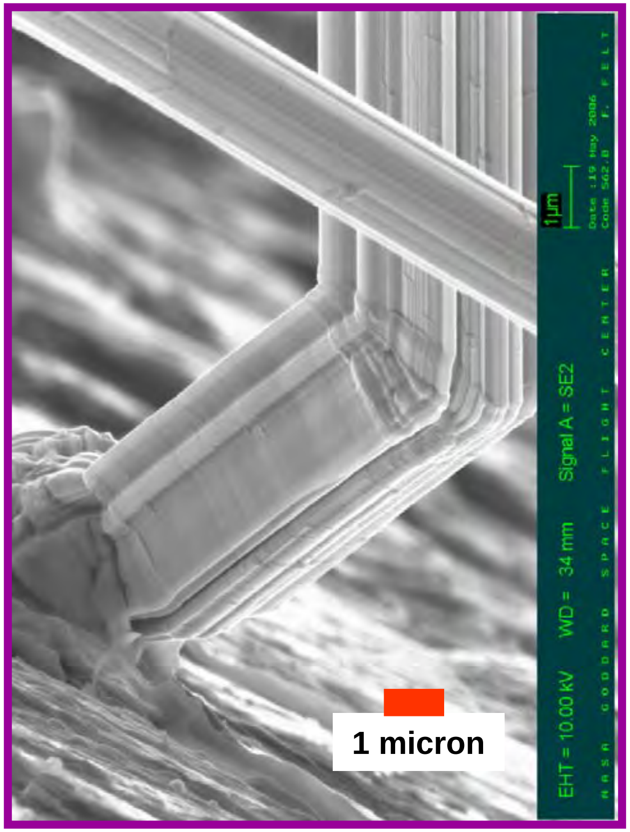
What are Metal Whiskers?

- **DESCRIPTION:**
  - **Hair-like, metallic crystals that UNPREDICTABLY grow out from a metal surface**
    - **Straight or kinked filaments, nodules, odd-shaped eruptions**
    - **Filaments usually have uniform cross section along entire length**
  - **Tin, Zinc and Cadmium coatings are most common sources**
  - **Whiskers are also less frequently seen on Indium, Silver, Lead, Gold and other metals**

- **GROWTH TIMELINE:**
  - ***Incubation:*** **Absence of growth may last hours to years**
  - ***Growth:*** **Accretion of metal ions at the ROOT of whisker NOT at tip**
    Long-range diffusion of metal atoms within coating
  - ***Growth Rate*: < 1 mm/yr (typical)**
    Highly variable (up to 9mm/yr reported)

- **LENGTH: Log-normal distribution [1]**
  ~1 mm or less (typical)
  Rarely up to 10 mm or more

- **THICKNESS: Log-normal distribution [1]**
  A few microns (typical)
  Range submicron to >10 um

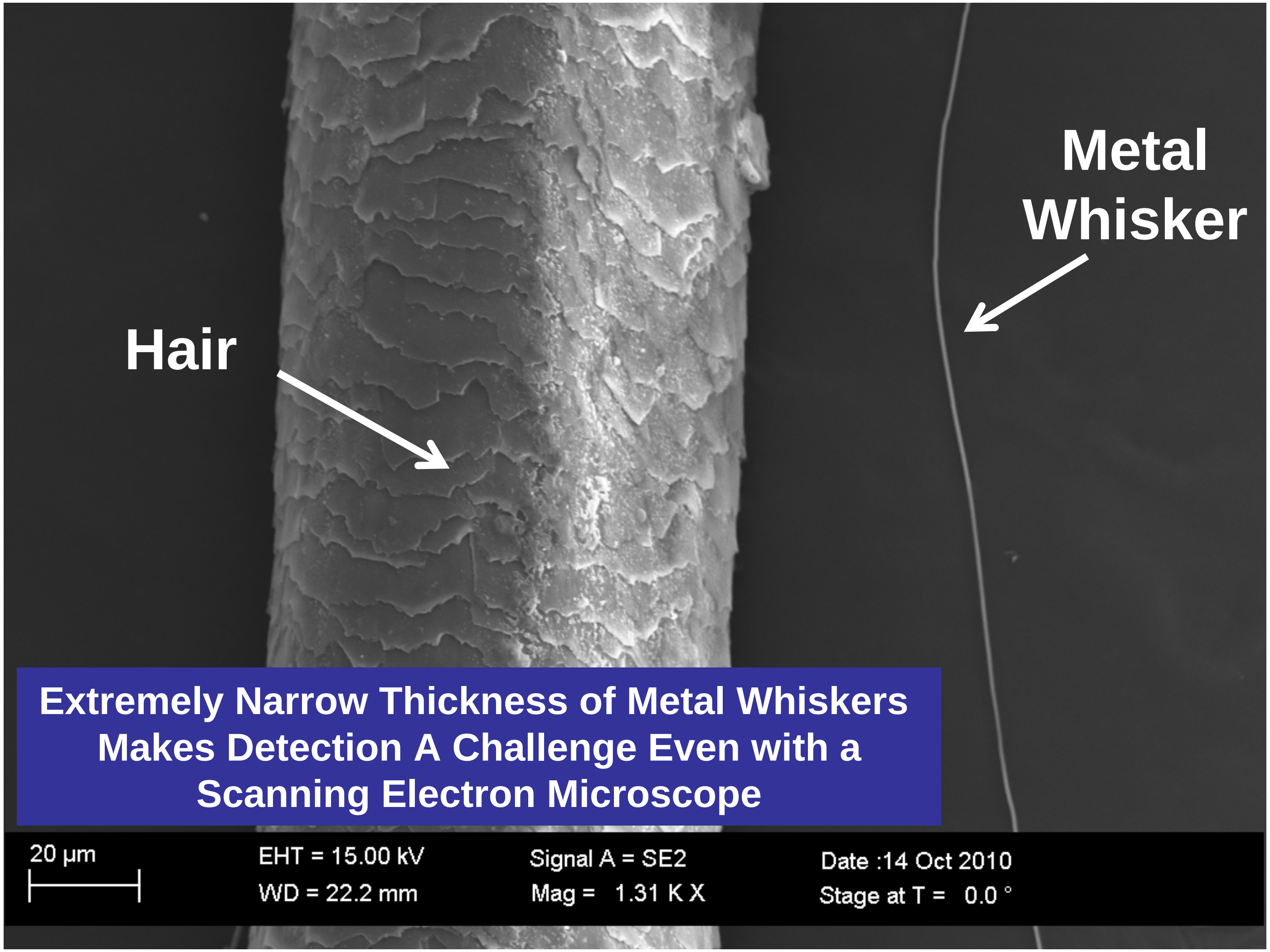


Tin Whiskers on Tin-Plated Electromagnetic Relay Terminals

[1] L. Panashchenko "Evaluation of Environmental Tests for Tin Whisker Assessment", MS Thesis, University of MD, 2009. http://hdl.handle.net/1903/10021

Human Hair vs. Metal Whisker

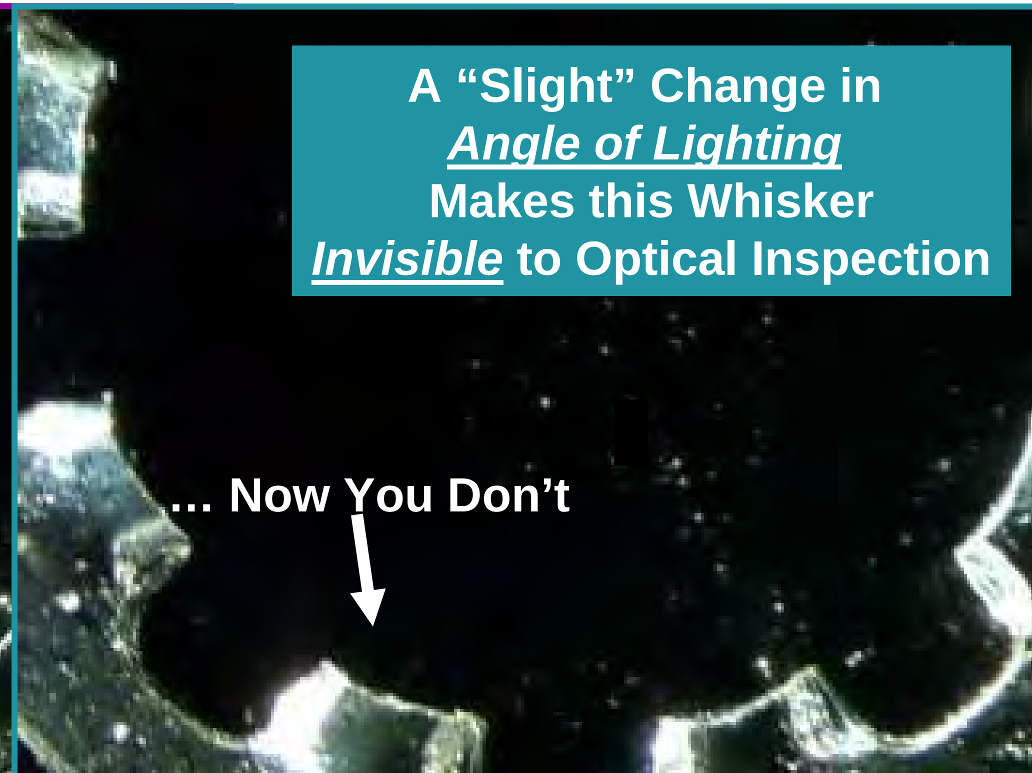
Metal Whiskers are commonly 1/10 to < 1/100 times thinner than a human hair!!!



Challenges with Optical Microscopy for Detecting Metal Whiskers

Videos with Guidance → *http://nepp.nasa.gov/whisker/video*

Tin-Plated Lock Washer



The absence of evidence is NOT evidence of absence

The Good News:

Not All Tin, Zinc or Cadmium Surfaces Will Grow Whiskers

(See Back Up Slide for Discussion)

The Bad News:

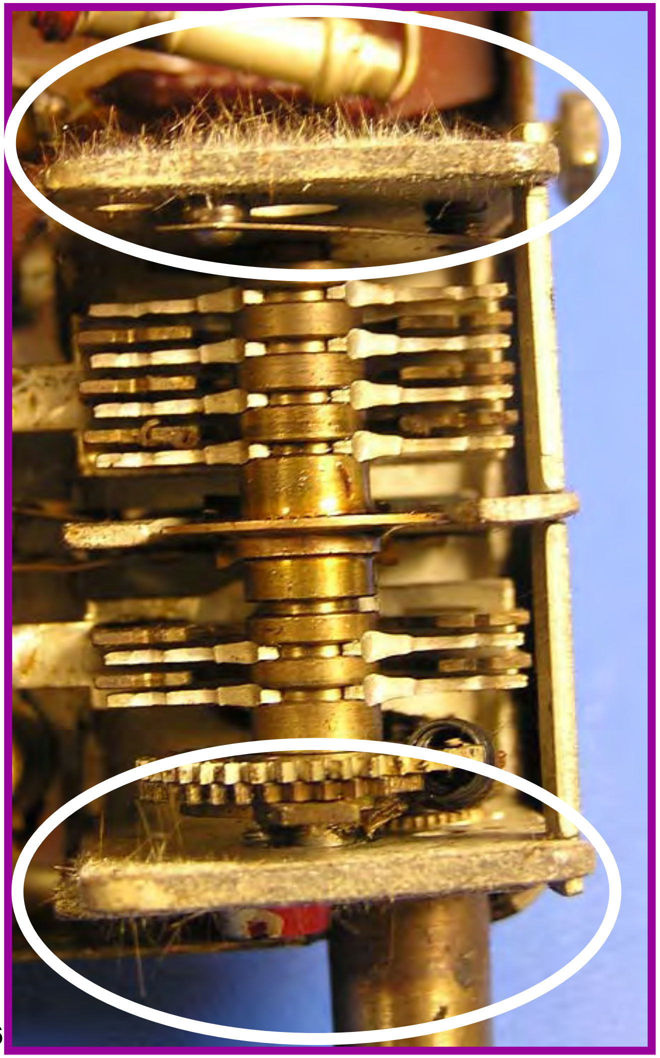
Current theories and test methods **DO NOT** have predictive power of the time-dependence of Whisker Density (# per area), Length or Thickness Distributions

A useful theory should identify what we must control to make confident predictions. Such a theory has remained elusive

Metal Whiskers
"The Early Years"

- **1946: Cadmium Whiskers[2]**
  - **H. Cobb (Aircraft Radio Corp.) published earliest known account of CADMIUM whiskers on cadmium-coated variable air capacitor plates.**
  - **Cd whiskers induced electrical shorting in military aircraft radio equipment. These events occurred during WW II (~1940 – 1945)**

- **1951: Tin and Zinc Whiskers**
  - **After learning of electrical failures from Cd whiskers, Bell Labs opted to use Tin and Zinc coatings.**
  - **But then Bell Labs reported electrical shorting caused by whiskers from these coatings too! [3]**



Tin Whiskers on 1960's Era Variable Air Capacitor
Similar to Types Described By Cobb in 1946

[2] H. Cobb, "Cadmium Whiskers", Monthly Rev. Am. Electroplaters' Soc., 33, 28, Jan. 1946
[3] K. Compton, "Filamentary Growths on Metal Surfaces – Whiskers", NACE, Mar. 1951

Whisker Resistant Metal Coatings
"The Quest"

- **1950s and 60's [4] [5]:**
  Bell Labs worked through the periodic table to determine whether co-deposition of some element with Tin would "inhibit" whiskering
  - ***Adding 0.5 - 1% by weight or more of <u>Lead (Pb)</u> into tin inhibits whiskering***
  - ***Alloying with metals other than Pb sometimes ENHANCES whiskering***

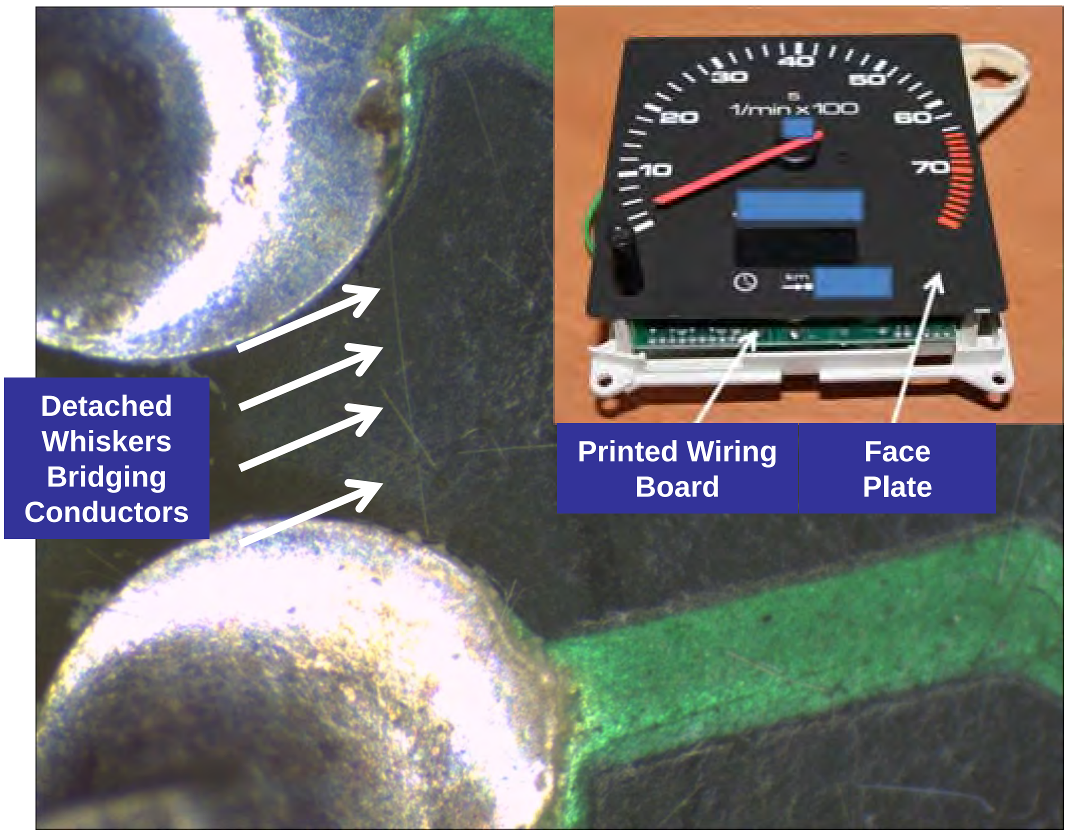
- **Since 1990s:**
  To inhibit whiskers most US MIL specs require adding Pb to tin coatings used near electronics
  - **For design margin, greater than 2% to 3% Pb by weight is usually specified**

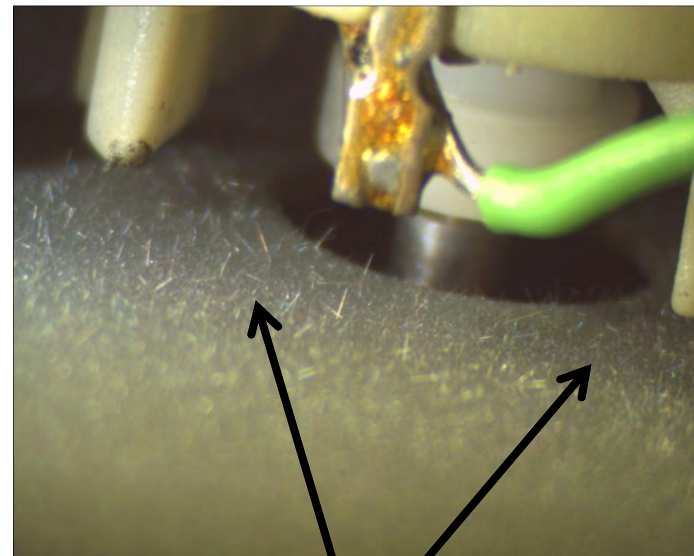
- **What additives quench Zn & Cd whiskers?**
  - **There appear to be no active efforts to investigate**
  - **Chromate conversion finishes DO NOT appear to stop whisker formation**

[4] S. Arnold, "Repressing the Growth of Tin Whiskers," *Plating*, vol. 53, pp. 96-99, 1966
[5] P. Key, "Surface Morphology of Whisker Crystals of Tin, Zinc and Cadmium," *IEEE Electronic Components Conference*, pp. 155-160, May, 1970

Zinc Whiskers on Tachometer
One of Several Recent Observations

- Tachometer (1980s vintage) face plate is made of **zinc-coated** iron
- Rear of face plate is infested with Zinc Whiskers
- Proximity of whiskers to adjacent electronics presents reliability risk

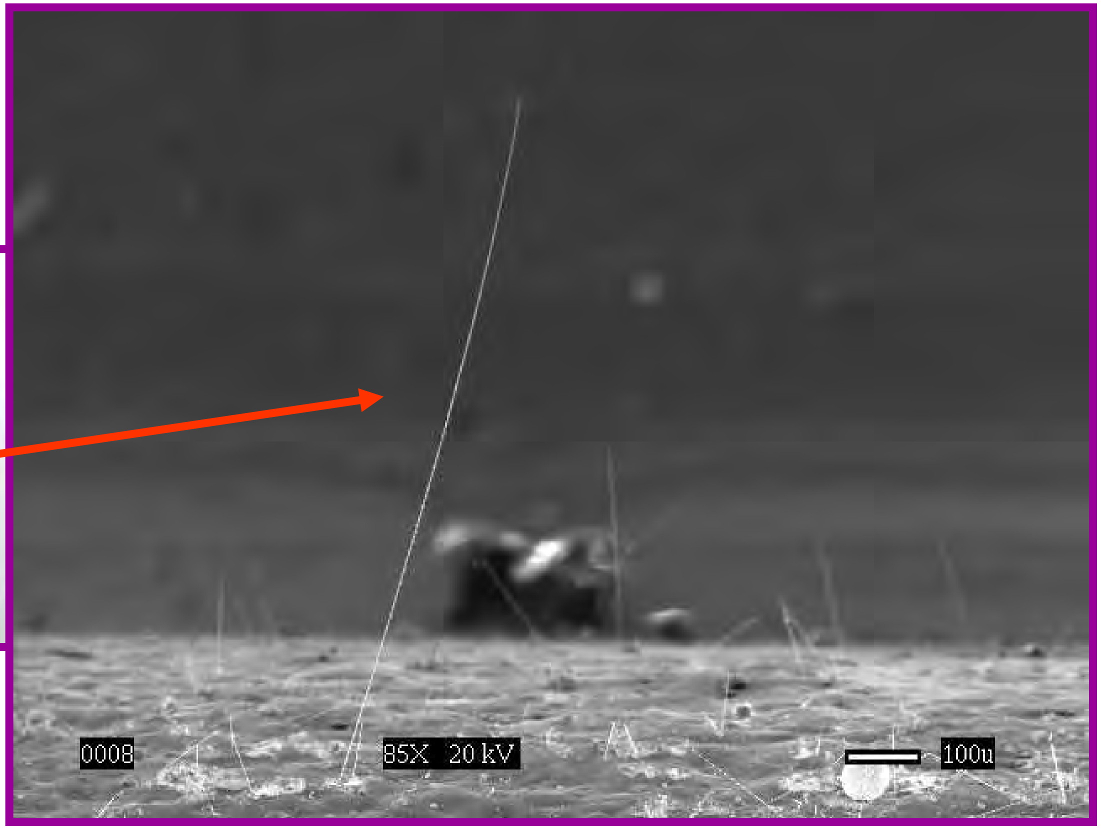




Rear of Face Plate is
Infested w/ Zinc Whiskers

Examples of Metal Whiskers

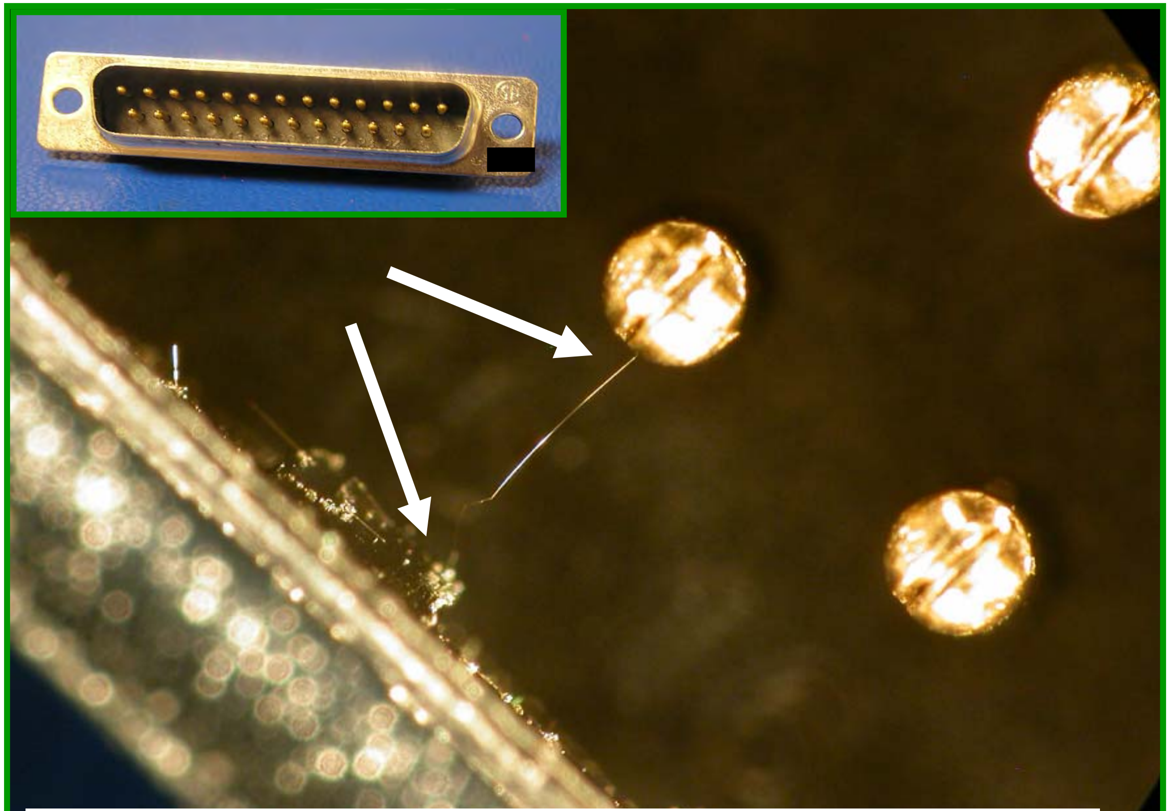
Zinc-Plated Steel Bus Rail
with Yellow Chromate Conversion Finish



Zinc whiskers grew up to several mm-long and shorted power to ground producing a metal vapor arc that disrupted the testing of a spacecraft system

Examples of Metal Whiskers

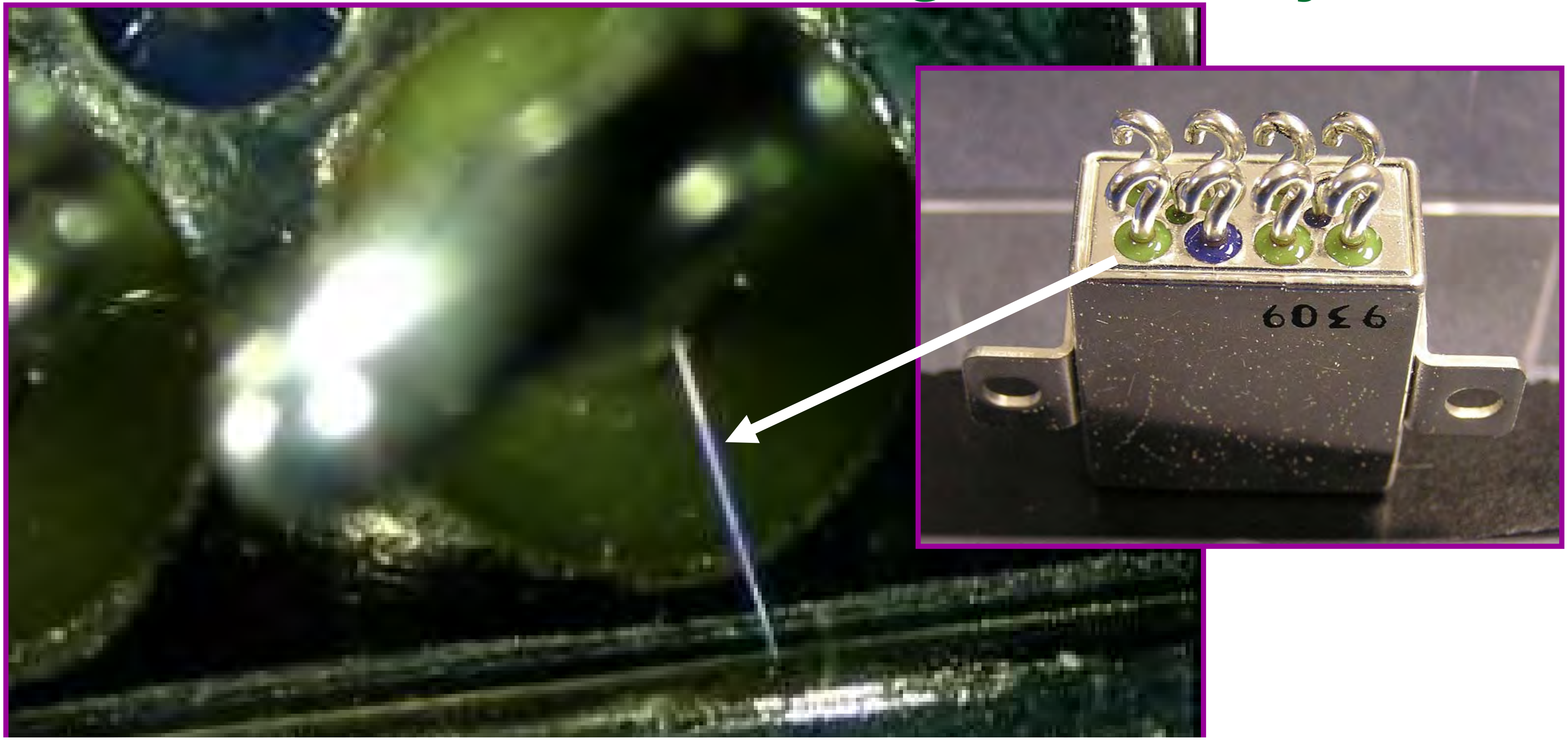
Tin-Plated D-Sub Connector Shell



Connector Advertised as "RoHS Compliant"

Examples of Metal Whiskers

Tin-Plated Electromagnetic Relay

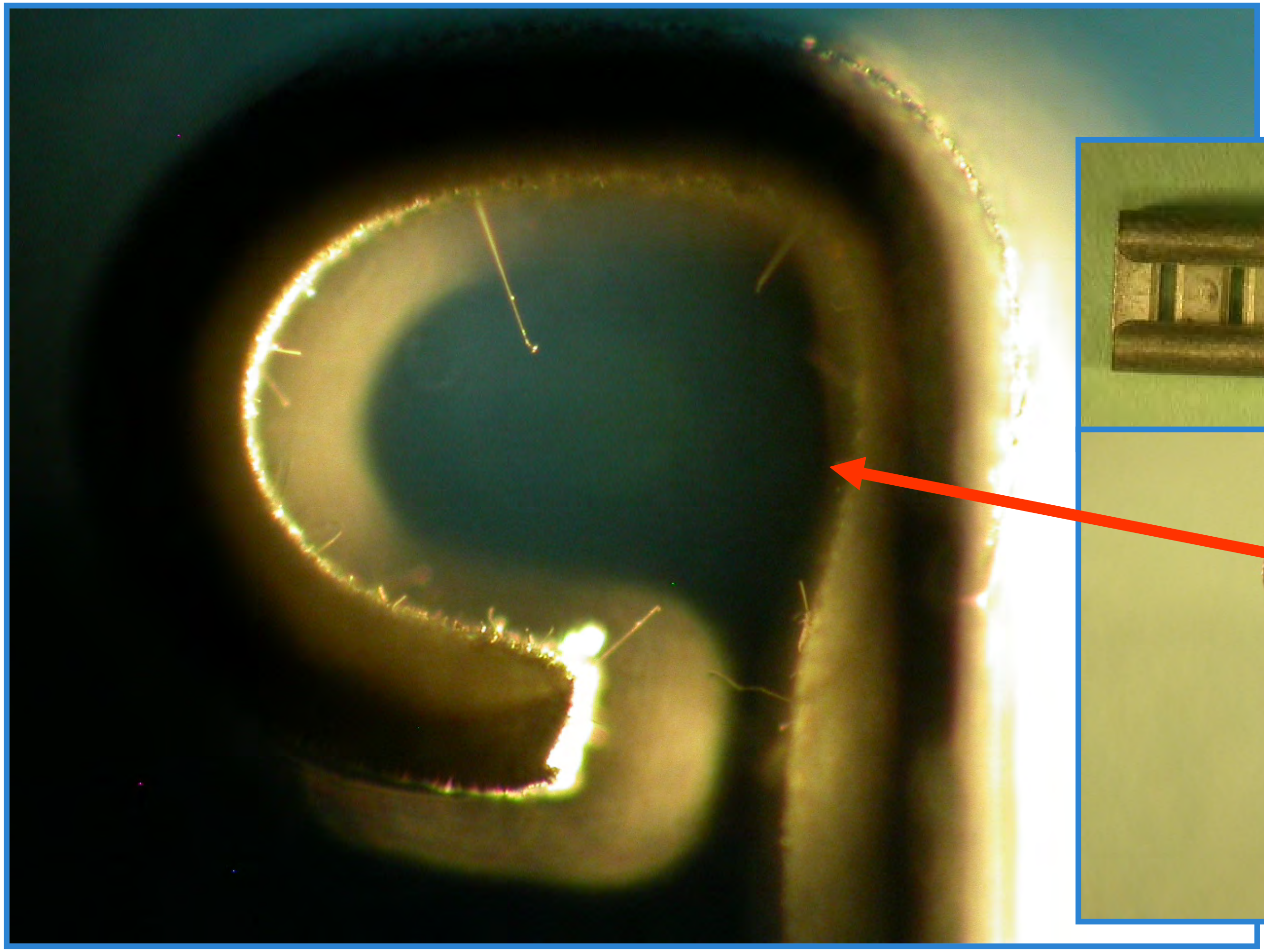


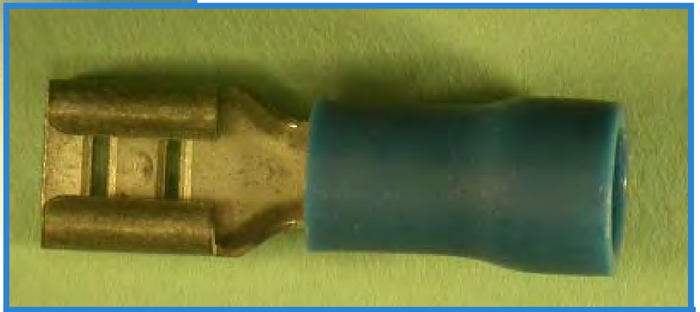
Procurement Specification for this Relay Required >2% Pb in the Tin-Plating, However, Pure Tin-Plated Relays were Supplied

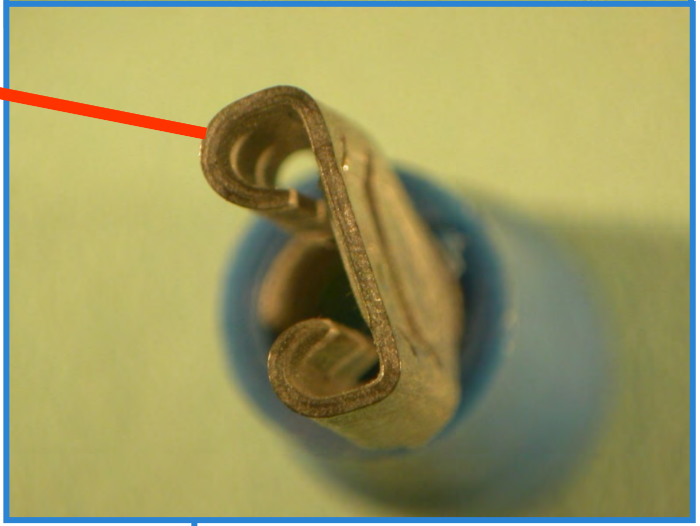
TRUST BUT VERIFY!!!

Examples of Metal Whiskers

Tin-Plated Terminal Lugs







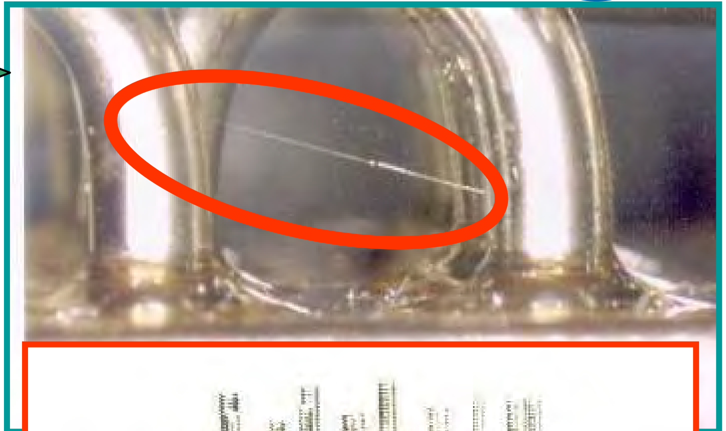
Examples of Metal Whiskers

Cadmium-Plated Connector Shell

Cadmium whiskers on a feedthru connector for a thermal-vacuum chamber
Cd whiskers grew to be several mm-long and produced electrical shorts from shell to connector pins that interrupted testing of a spacecraft system

Electrical Properties of Metal Whiskers

Electrical Short Circuits



$$\boxed{R = \frac{\rho \cdot L}{A}}$$

Where
R = resistance of whisker
ρ = resistivity; L = length;
A = cross sectional area

- **Continuous short if current** $I_{whisker} < I_{melt}$
- **Intermittent short if** $I_{whisker} > I_{melt}$
- ***Metal Vapor Arc!!!*** ***See Discussion***
  Up to HUNDREDS of AMPERES can be Sustained!!!

Debris/Contamination

- **Dislodged whiskers become foreign object debris**
  - **Produce Shorts in Areas REMOTE From Whisker Origins**
    Example: zinc whiskers are often detached from zinc-coated raised floor tiles by physical handling. Once detached they are re-distributed by air currents into nearby electronic assemblies

http://nepp.nasa.gov/whisker/reference/tech_papers/2004-Brusse-Zn-whisker-IT-Pro.pdf

Whisker Melting Current and Voltage (in Vacuum)

$$I_{melt,vac} = \left[\frac{2\sqrt{Lz}T_0}{R_0}\right]\cos^{-1}\left(\frac{T_{amb}}{T_{melt}}\right)$$

$$V_{melt,vac} = 2\sqrt{Lz}\sqrt{T_{melt}^{2} - T_{amb}^{2}}$$

– ***Where*** ***$Lz \sim 2.45 \times 10^{-8}$ $(V/K)^2$ is the Lorenz number, T_{melt} = melting temperature, T_{amb} = ambient temperature, T_0 = ref. temp, R_0 = whisker resistance at ref. temp***

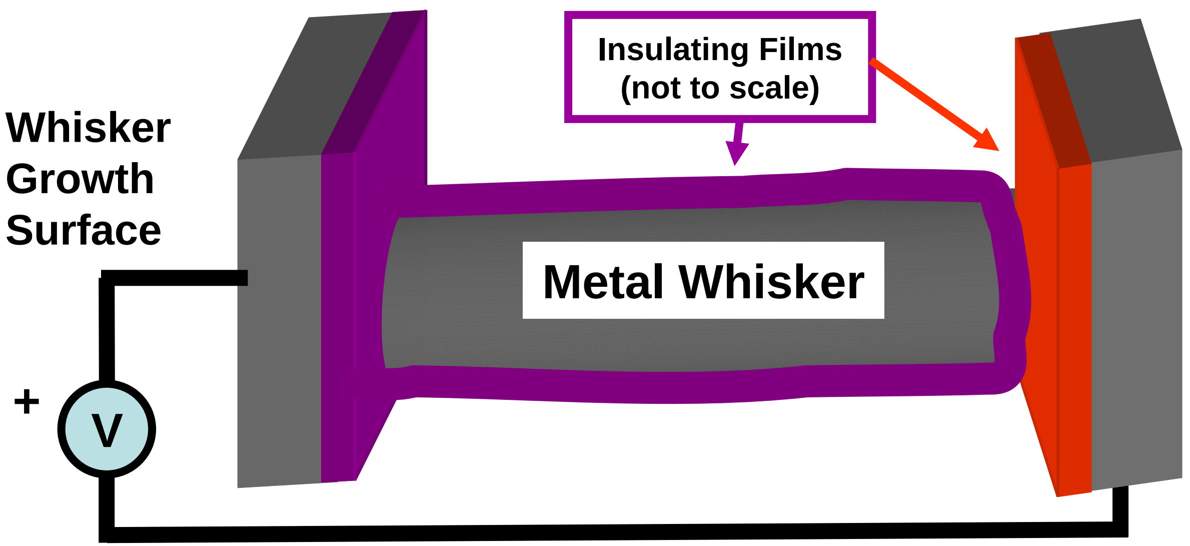
Material	***T_{melt}***	***$I_{melt,\ vac}$*** for To = Tamb =293.15K	***$V_{melt,\ vac}$*** for Tamb =293.15K
Tin	505.1K	87.3 mV / R_0	***129 mV***
Cadmium	594.2K	96.8 mV / R_0	***162 mV***
Zinc	692.7K	104.1 mV / R_0	***196 mV***

If $V_{whisker} > V_{melt}$
Then the Whisker will Fuse Open

But there is MORE to this story

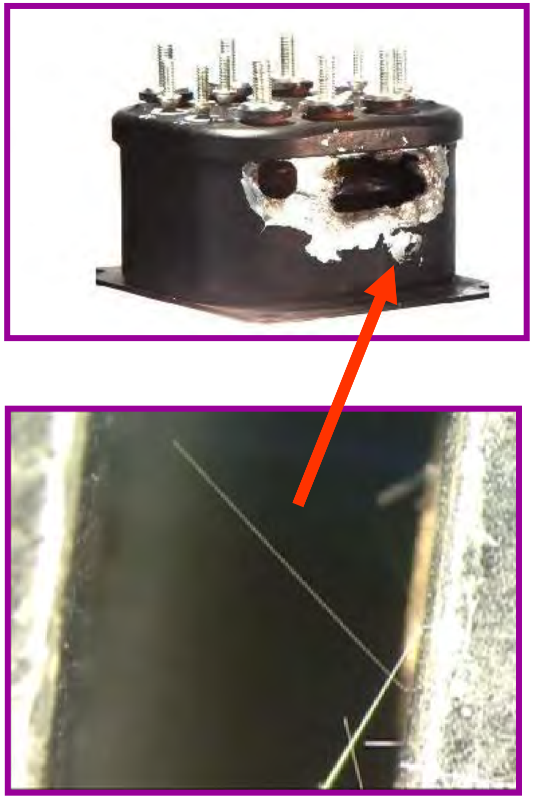
Metal Whiskers and Adjacent Conductors Accumulate Insulating Films

- Electrically insulating films form on metal whiskers and adjacent conductors
  - Depending on the environment → Oxides, sulphides, sulphates, chlorides, etc.
- These films act as barriers to electrical current flow UNLESS applied voltage exceeds "dielectric breakdown" strength of the combined films
  - Direct **MECHANICAL** contact does NOT guarantee **ELECTRICAL** contact
  - Courey (NASA), et al have measured the breakdown voltage of films on tin whiskers
    - V_{BD} fit a probability distribution with a wide range (~60mV to >45Volts)
  - Insulating effects of these films are important to recognize
    - May fool failure analysts when bench testing (e.g., ohmmeter) to detect shorts
    - May explain survival of some electronics in the field despite whisker infestation



Sustained Metal Vapor Arcing Initiated by Metal Whisker

- When a metal whisker shorts two conductors at different potentials, a sustained arc capable of carrying *HUNDREDS OF AMPERES* can occur if
  - Current is high enough to vaporize the whisker (i.e., create metal gas) AND,
  - Voltage is high enough to ionize the metal gas
- Parameters affecting metal vapor arc ignition and sustainment include:
  - Arc Gap Distance
  - Voltage across gap
  - Current available from power source
  - Atmospheric pressure
    - *Vacuum (i.e., low pressure) is NOT required*
    - Lower pressures will reduce the threshold voltage and current required for arcing (i.e., "air" can act as an arc quencher)
  - Material available to supply fresh ions to fuel the arc

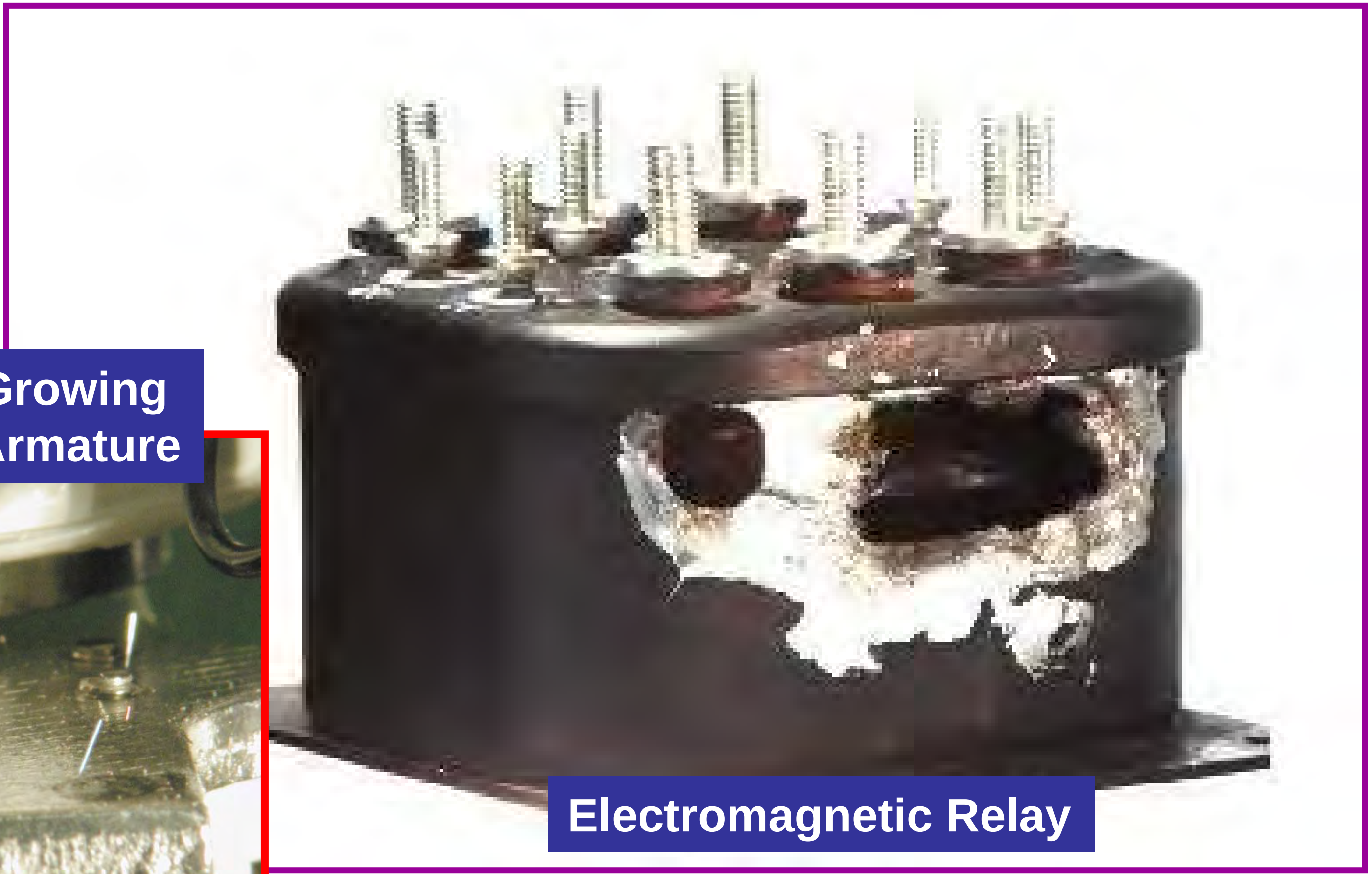


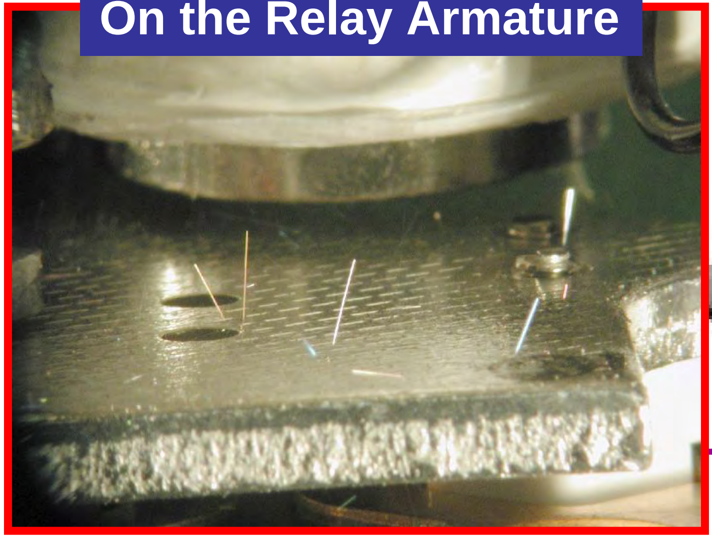
Tin Whiskers Growing on Armature Of Relay Produced Metal Vapor Arc Resulting in Destruction of Device

NOTE: It is the METAL VAPOR that serves as medium that sustains the arc

Metal Vapor Arcing Initiated by Metal Whiskers In a Military Aircraft

http://nepp.nasa.gov/whisker/reference/tech_papers/davy2002-relay-failure-caused-by-tin-whiskers.pdf

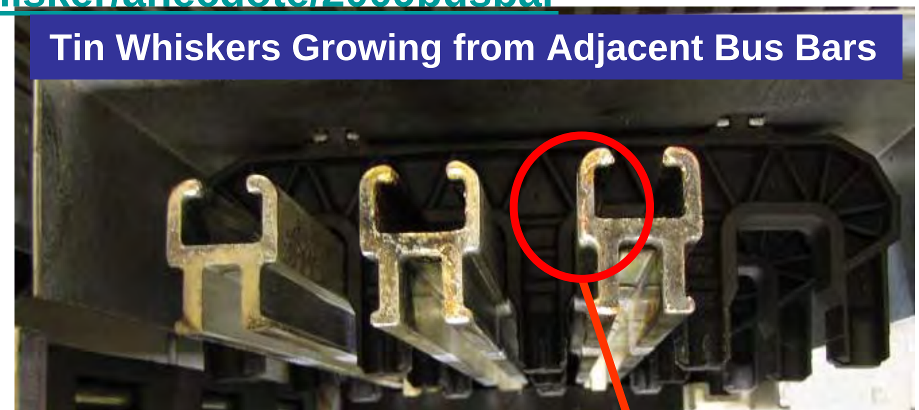




Metal Vapor Arcing
Initiated by Metal Whiskers
In a Paper Mill

http://nepp.nasa.gov/whisker/anecdote/2009busbar

Arcing Damage in an Equipment Cabinet
At least 3 separate events
Recorded at this one facility

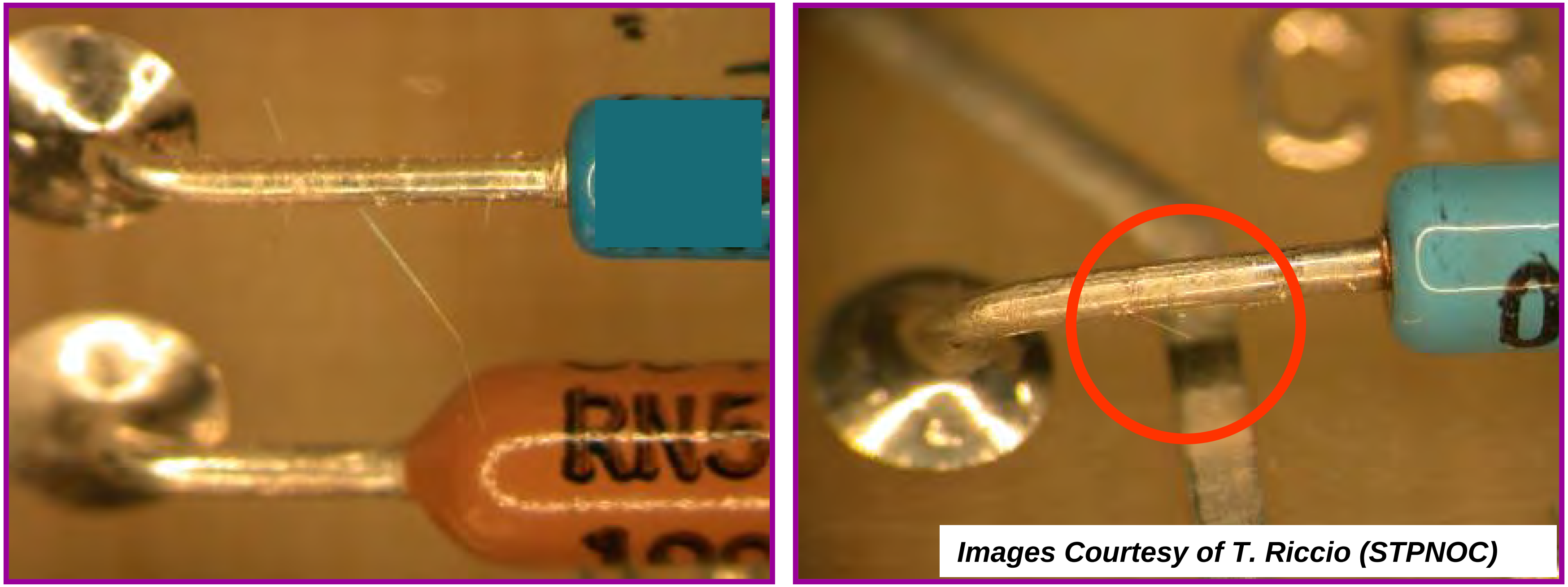


Tin Whiskers Growing from Adjacent Bus Bars

Tin Whiskers Growing
On Bus Bars

A Case for Whisker Mitigation Strategies?

Tin Whiskers on Tin-Plated Axial Leaded Diodes



Images Courtesy of T. Riccio (STPNOC)

- Diode Leads were **NOT Hot Solder Dipped** prior to assembly; thus leaving large surface area of pure tin coating prone to whisker growth
- PWB and components were **NOT Conformal Coated**; thus leaving adjacent conductors exposed to bridging by whisker growth

Some Whisker Mitigation Strategies

*Mitigation – to make **less** severe or painful*
Merriam-Webster Dictionary

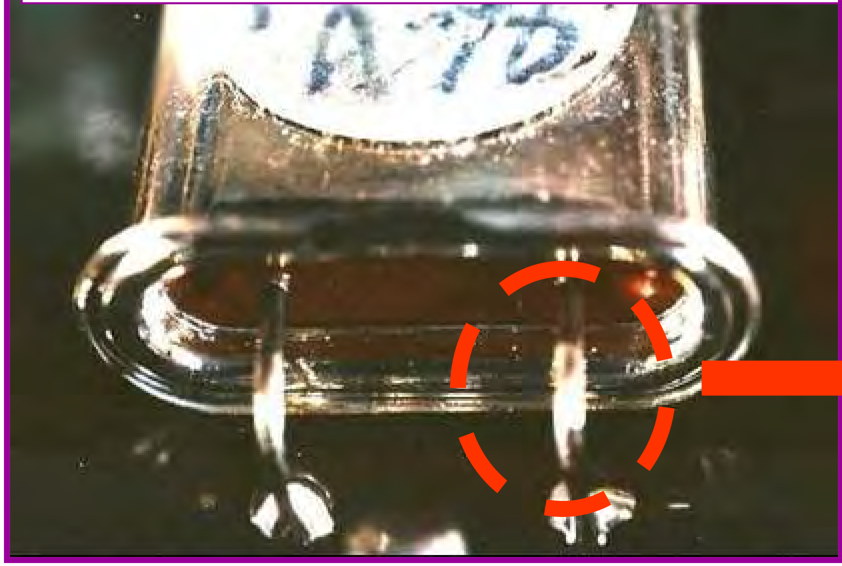
Risk "Mitigation" ≠ Risk "Elimination"

- **Avoid Use of Whisker Prone Surface Finishes**
  - *"Trust, But VERIFY" Certificates of Conformance!*
  - Perform independent materials composition analysis using X-ray Fluorescence (XRF), Energy Dispersive X-ray Spectroscopy (EDS), etc.
- **Remove/Replace Tin Finishes When Practical**
  - Hot Solder Dip using lead-tin (Pb-Sn) solders
  - Follow the Principle of "First, Do No Harm"
- **Use Conformal Coat or Other Electrically Insulating Barriers**
  - Benefit #1: When applied on top of a whisker prone surface, conformal coat can sometimes keep whiskers from pushing through
  - Benefit #2: When applied to a distant conductor, can block whiskers from electrically shunting distant conductors
  - Benefit #3: Provides insulating barrier against loose conductive debris

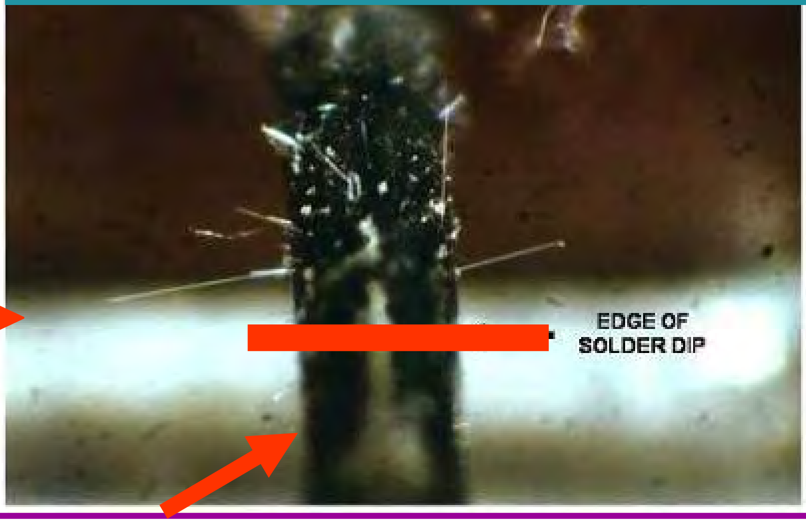
Hot Solder Dip
Benefits & Limitations

Field Failure ONE Year **After Assembly**

Crystal with Tin-Plated Kovar Leads (with Nickel Underplate)



Tin Whiskers (~60 mils) Grew on *NON-Dipped* Region Shorting to Case Causing Crystal to Malfunction



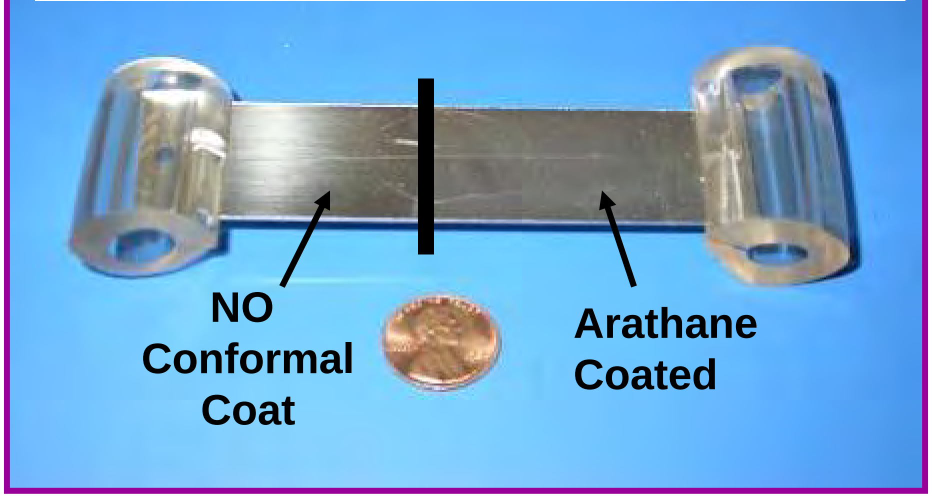
- Leads were *Hot Solder Dipped* (Sn63Pb37) *within 50 mils* of Glass Seal BEFORE Mounting to enhance solderability
- Dip was not 100% of leads due to concerns of inducing harm to glass seal

- No Whiskers on Hot Solder Dipped Surface
- ABUNDANT whiskers on the NON-Dipped Surface

NASA Goddard Whisker Mitigation Study
Conformal Coat (Arathane 5750* Polyurethane)
~11 Years of Office Ambient Storage

- **Specimens:**
  - 1” x 4”x 1/16” Brass 260
  - Tin-Plated 200 microinches
  - A few intentional scratches created after plating to induce localized whisker growth
- **Conformal Coating:**
  - Arathane 5750 on ½ of sample
  - Nominal Thickness = 2 mils
  - Locally THIN Regions also examined
- **Storage Conditions:**
  - Office Ambient ~ 11 years

Parameters were Chosen in Hope of Producing Samples that are Prolific Whisker Growers!!!



***** *Arathane™ 5750 formerly known as Uralane™ 5750***

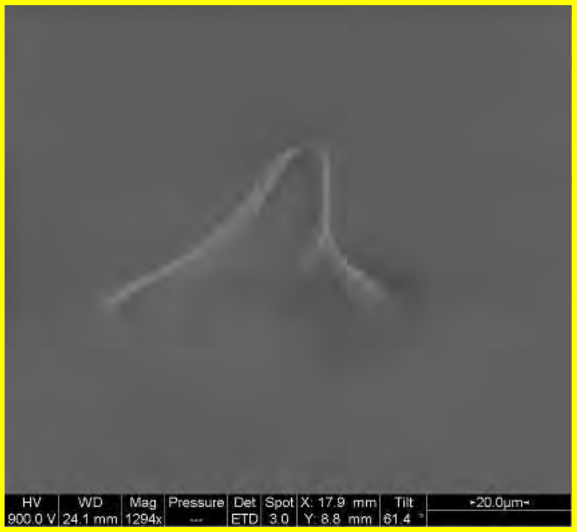
NASA Goddard Whisker Mitigation Study

Arathane 5750 Conformal Coat –
11-Years of Office Ambient Storage

2 Mils Arathane = Very Effective

Whiskers Completely Entrapped Under the Coating → Euler Buckling

~0.5 Mils Arathane = Less Effective



Whisker "Lifting" Coating into Shape of Circus Tent, But Not Yet Penetrating

~0.1 Mils Arathane = Not Effective

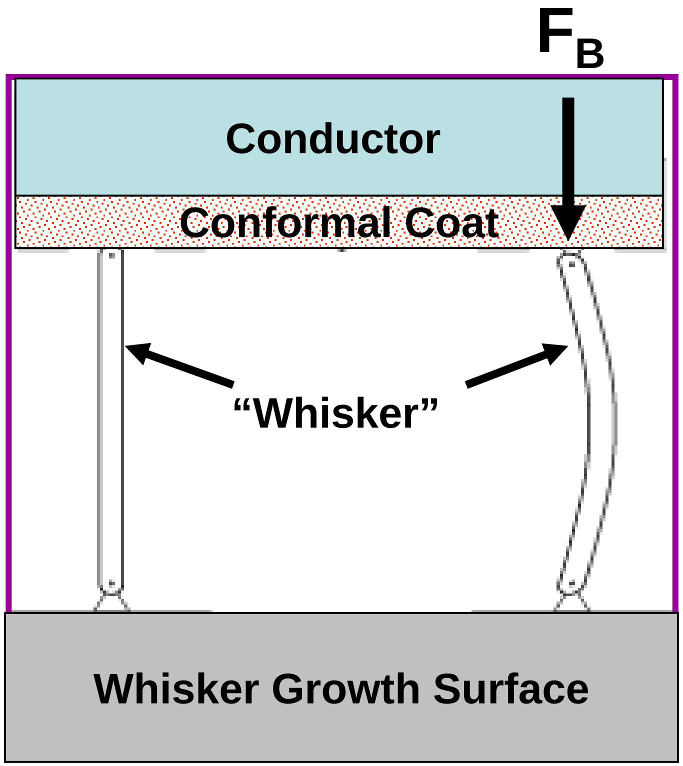
Whiskers Breaking Through "Thin" Coating

Euler Buckling

Axial Force Required to Buckle a Metal Whisker

$$F_B = \frac{\pi^2 EI}{(KL)^2} \approx \left(\frac{\pi^3 \cdot E}{32}\right)\left(\frac{d^4}{L^2}\right)$$

E = Young's Modulus of whisker material,
I = Area Moment of Inertia,
(e.g. I = π d^4 / 64 for circular cross section)
L = Length of whisker,
K = Column Effective Length Factor
K = 0.5 for whisker fixed at both ends
K = 0.7 for fixed at one end, pinned at other

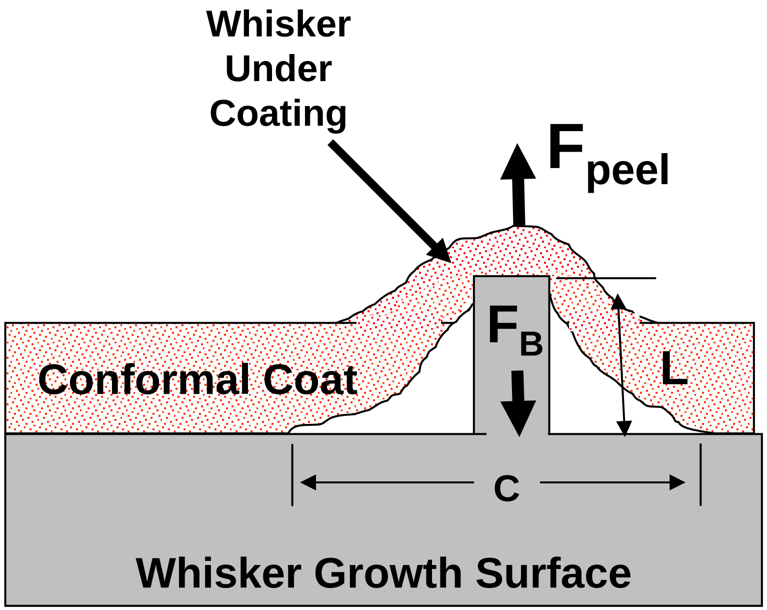


Whiskers Lift and Peel Conformal Coat Until Whisker Buckles <u>OR</u> Coating Fails (F_{peel} vs. F_{Buckle})

- **As whisker first emerges it is short and stiff thus $F_B > F_{peel}$ and whisker begins to lift the coating forming a "circus tent" with height L = length of whisker;**

- **"Tent" joins the surface at a circle of circumference C ~ 2πQL,**
  - **Q describes the details of tent-like shape**

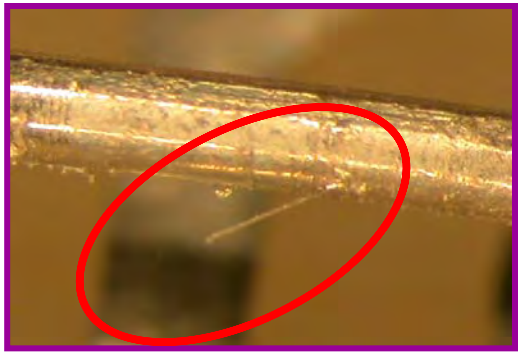
- **To peel conformal coating up and away from the surface, one needs to apply a force (F_{peel}) proportional to the circumference:**
  - **$F_{peel} = \Phi * C = 2 \text{ pi } Q \, \Phi \, L$**
    Φ = peel strength of material which describes the adhesion of the coating to the tin, and the effect of the separation angle. It also depends on the rate at which the coating is peeled away.



Arathane 5750 has better self-cohesion than adhesion to a tin surface

Will Whiskers Buckle Before Puncturing the Coating on a Distant Surface?

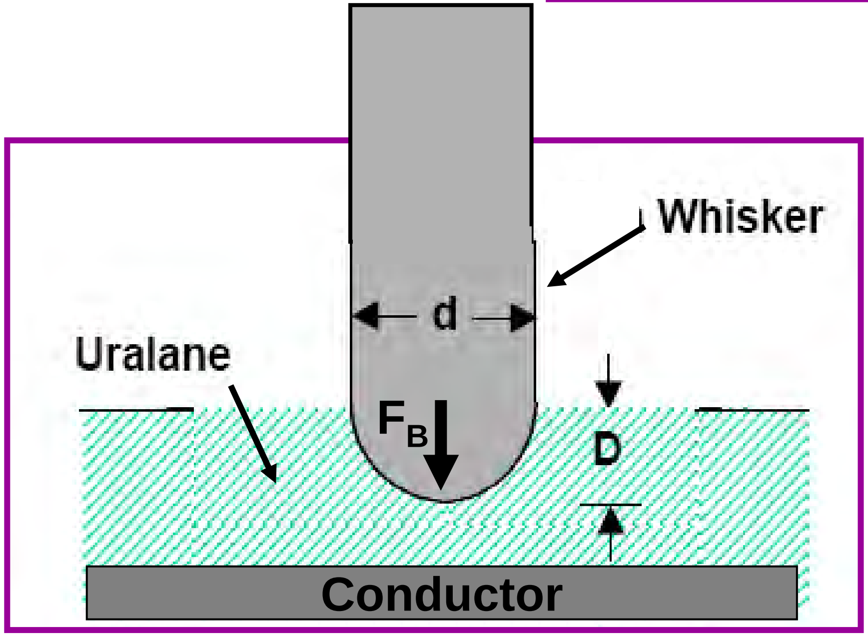
- The displacement of the conformal coat due to a whisker pushing against the coating is:



$$D = \left(\frac{1-\nu^2}{E_{coat}}\right)\left(\frac{F_B}{d}\right) \approx \left(\frac{\pi^3}{32}\right)\left(1-\nu^2\right)\left(\frac{E_W}{E_{coat}}\right)\left(\frac{d^3}{L^2}\right)$$

Where

- D = Displacement of conformal coat
- ν = Poisson's ratio
- E_{coat} = Young's Modulus of coating
- E_W = Young's Modulus of Whisker
- d = "Diameter" of whisker
- L = Length of whisker
- F_B = Euler Buckling Strength of the whisker



Effects of Conformal Coating

- Conclusion 1:
  No whiskers have penetrated 2 mils of Arathane 5750 after 11 years
  – Despite samples being capable of forming approximately 50 whiskers/mm^2 on coated areas greater than 600mm^2
  – Whiskers still nucleate beneath the conformal coating

- Conclusion 2:
  *Whiskers have penetrated when Arathane 5750 is **thin** (~0.1mil or less)*
  – Thinner coatings are more prone to whisker puncture
  – Conformal coating processes can leave "weak zones". *Understand YOUR PROCESSES*
    - Shadowing effects may prevent complete coverage when applying coating
    - Coating may flow/thin prior to completion of cure

- Conclusion 3:
  Even "Poor" Coatings Can Offer Some Protection
  – Long whiskers bend easily (Euler Buckling) and are less likely to re-penetrate even thin conformal coat applied on a distant conductor.
  – Conformal coat protects against a conductive bridge from detached whiskers lying across a pair of coated conductors

Contact Information

Jay Brusse

Dell Perot Systems at
NASA Goddard Space Flight Center

Jay.A.Brusse@nasa.gov

Work Performed in Support of the NASA Electronic Parts and Packaging (NEPP) Program

NASA Tin and Other Metal Whisker WWW Site

http://nepp.nasa.gov/whisker

Backup Slides

"The Five Stages of Metal Whisker Grief"

By Henning Leidecker

Adapted from Elisabeth Kubler-Ross in her book "On Death and Dying", Macmillan Publishing Company, 1969

Denial

"Metal whiskers?!? We ain't got no stinkin' whiskers! I don't even think metal whiskers exist! I KNOW we don't have any!"

Anger

"You say we got whiskers, I rip your $%#@ lungs out! Who put them there --- I'll murderize him! I'll tear him into pieces so small, they'll fit under one of those *^&$#% whiskers!"

Bargaining

"We have metal whiskers? But they are so small. And you have only seen a few of them. How could a few small things possibly be a problem to our power supplies and equipment? These few whiskers should be easy to clean up."

Depression

"Dang. Doomed. Close the shop --- we are out of business. Of all the miserable bit joints in all the world, metal whiskers had to come into mine... I'm retiring from here... Going to open a 'Squat & Gobble' on the Keys. "

Acceptance

"Metal whiskers. How about that? Who knew? Well, clean what you can. Put in the particle filters, and schedule periodic checks of what the debris collectors find. Ensure that all the warrantees and service plans are up to date. On with life."

1980s/1990s Zinc Whiskers Lead to FDA Class I Apnea Monitor Recall

http://nepp.nasa.gov/whisker/reference/tech_papers/1994-downs-zinc-whisker-liability.pdf
http://www.fda.gov/bbs/topics/ENFORCE/ENF00065.html

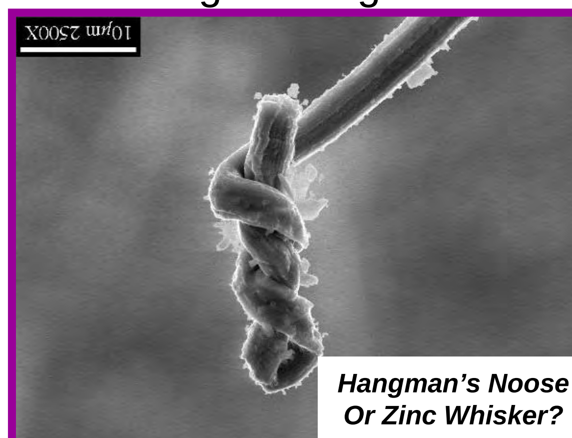
- **FDA Class I recall >1500 apnea monitors made by Electronic Monitors, Inc**
  - Failure Mode: Failure to alarm due to defective time delay switch
  - Failure Mechanism: Zinc whiskers from zinc-plated switch components cause low voltage short circuit
  - Investigation: *It took ~4 years + numerous experts before zinc whiskers recognized as cause of failure due to lack of familiarity with and complexity of identifying metal whiskers*
- **Bankruptcy and Lawsuits**
  - Electronic Monitors sues Electro Switch and their suppliers of zinc-plated internal structures for product liability, negligence, fraud, breach of warranty, etc.
  - Electronic Monitors files for bankruptcy as a result of losses during this saga
  - Case settled out of court
  - Electronic Monitors never recovered; company folded

The Phenomenon of Zinc Whisker Growth and the Rotary Switch

(or, How the Switch Industry Captured the Abominable Snowman)

by Jay R. Downs,
Spear, Downs and Judin, Dallas
and R. Michael Francis,
Electro Switch Corp., Raleigh, N.C.

Metal Finishing Magazine, August 1994, pp. 23-25



Hangman's Noose Or Zinc Whisker?

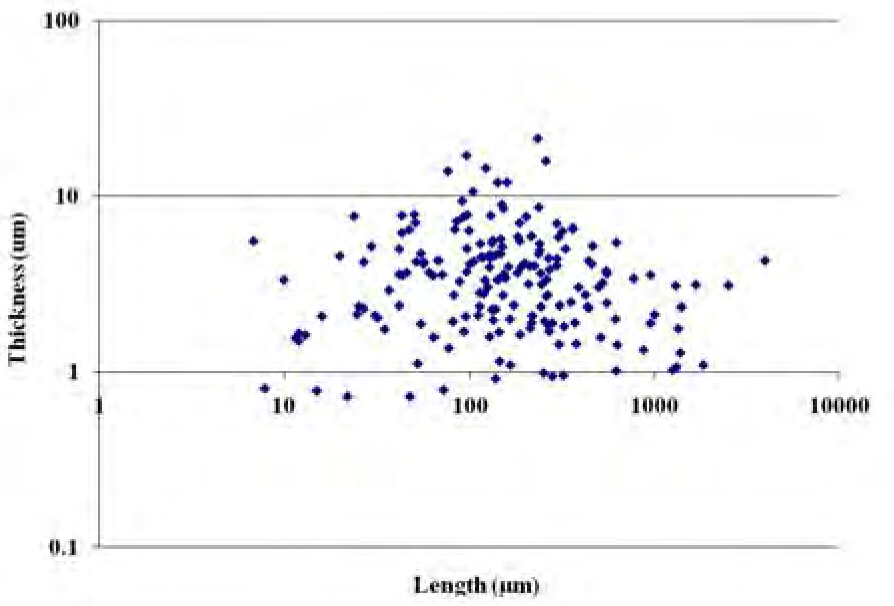
Tin Whisker Growth Statistics

Sample = Tin-plated brass coupon (~9 years after plating)

- Whisker density (# per area) was measured on 30 random areas ~0.64mm^2 each
- Whisker lengths and thicknesses were measured for 187 whiskers
  - **<u>Lognormal</u> distribution fits both length and thickness** **

Whisker growth metric (units)	Distribution type	μ	σ	Median
Density (#/mm^2)	Normal (Gaussian)	54	20	50
Length (μm)	Lognormal	5.01	1.15	150
Thickness (μm)	Lognormal	1.17	0.67	3.38

Note: μ=ln(median); σ=(ln(1+variance/mean^2)) $^{1/2}$

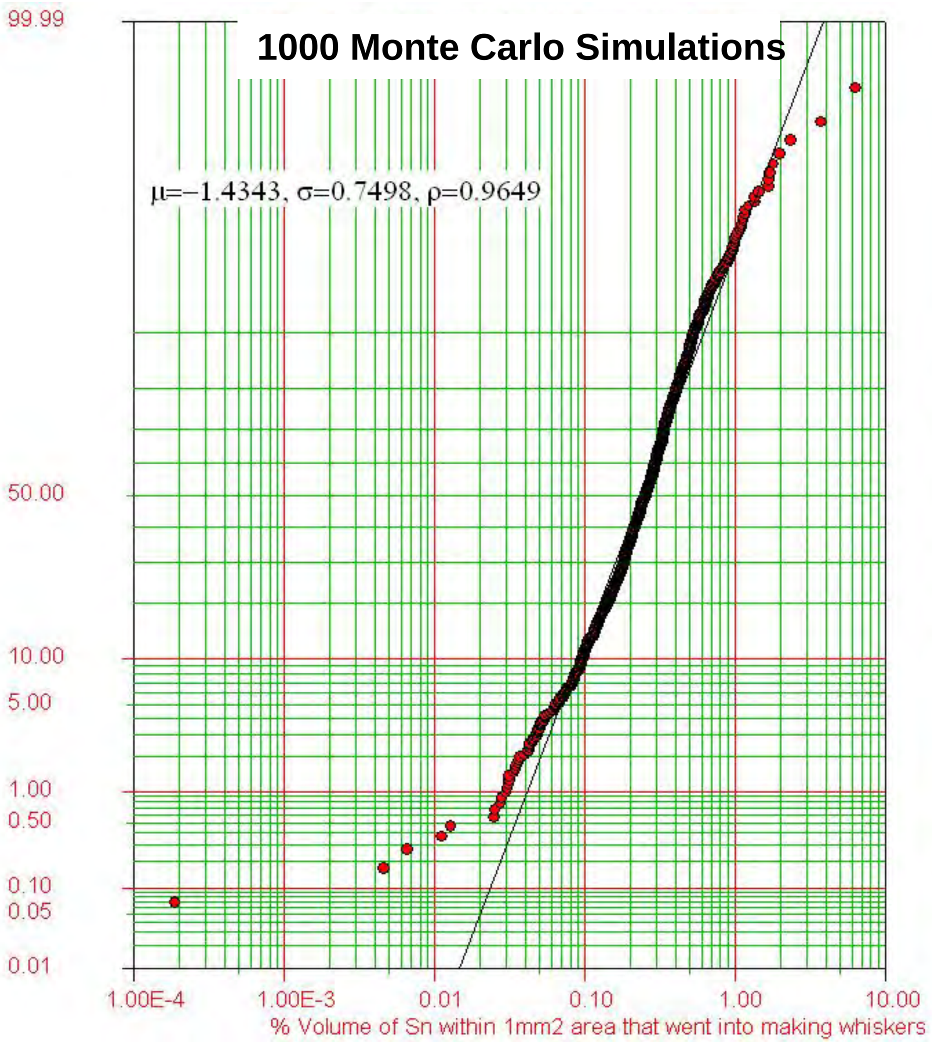


- Graph represents lack of correlation between whisker length and thickness
  - Meaning that whiskers of any thickness can grow to any length
  - Thus, thick whiskers can grow dangerously long (Euler Buckling of whisker ∝ thickness^4)

***** L. Panashchenko "Evaluation of Environmental Tests for Tin Whisker Assessment", MS Thesis, University of MD, 2009.***
http://hdl.handle.net/1903/10021

How Much Sn is Consumed in
Growing a Dense Population of Whiskers?

- Local depletion of tin surrounding a whisker root is rarely observed
- Long-range diffusion of tin supplies the material to form a whisker
- Monte Carlo simulation based on measured distributions was used to calculate tin consumption. Parameters used:
  - Whisker density (#/area)
  - Whisker lengths
  - Whisker thicknesses
  - Tin coating thickness ~6.5µm
  - Assumed area 1mm^2
- Results of simulation:
  - Median tin consumption is ~0.24% of the available Sn in the film
  - This agrees with lack of visual depletion of Sn



Circuit to Measure Resistance of a Metal Whisker

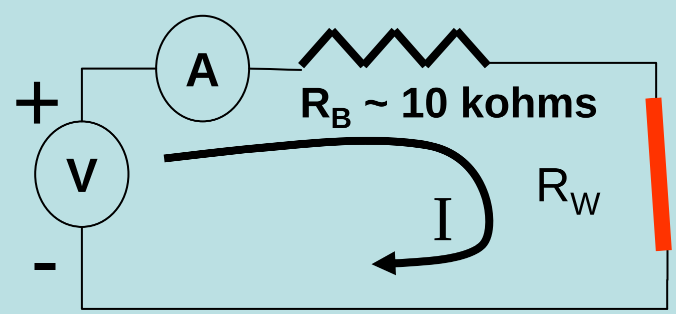
- **Use of a simple "Ohmmeter" to measure the resistance of a metal whisker is NOT preferred**
  - **Ohmmeter may supply $V_{out} < V_{breakdown}$ for the insulating films (oxides, moisture) that form on a metal whisker**
  - **Ohmmeter may supply $V_{out} > V_{melt}$ causing the whisker to melt before resistance can be measured**

- **Instead, a variable power supply and a ballast resistor can be used to overcome the above complications**
  - **Adjust $V_{out} > V_{breakdown}$ of insulating films on whisker**
  - **When $V_{out} > V_{breakdown}$, R_B quickly drops $V_{whisker} < V_{melt}$**

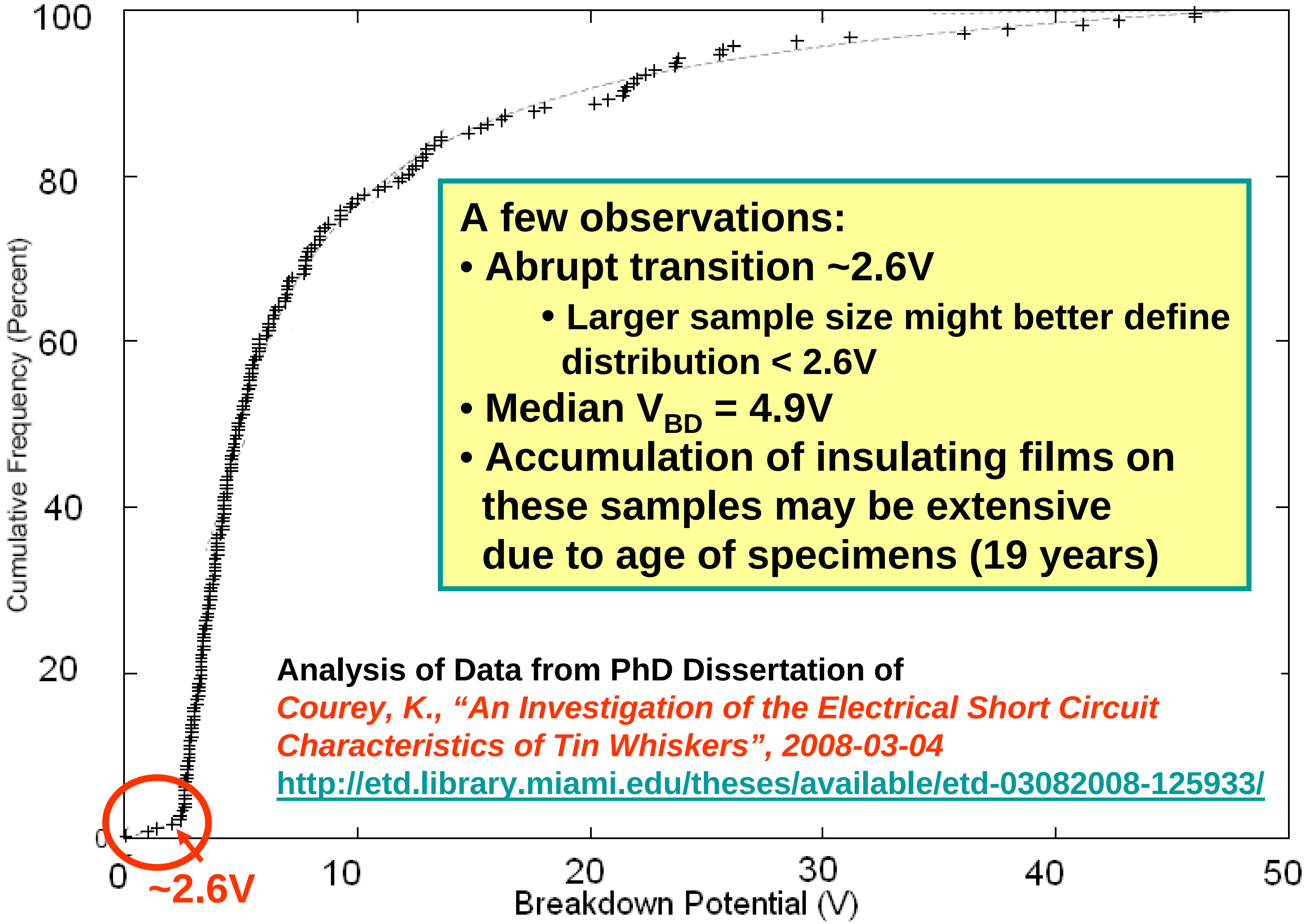
Circuit to measure R_w

$$\boxed{R_W = \frac{V - IR_B}{I}}$$

Choose R_B such that $V_{whisker} < 80\%\ V_{melt}$



Breakdown Potential of Insulating Films on 200 Tin Whiskers from ~19 Year Old Hardware

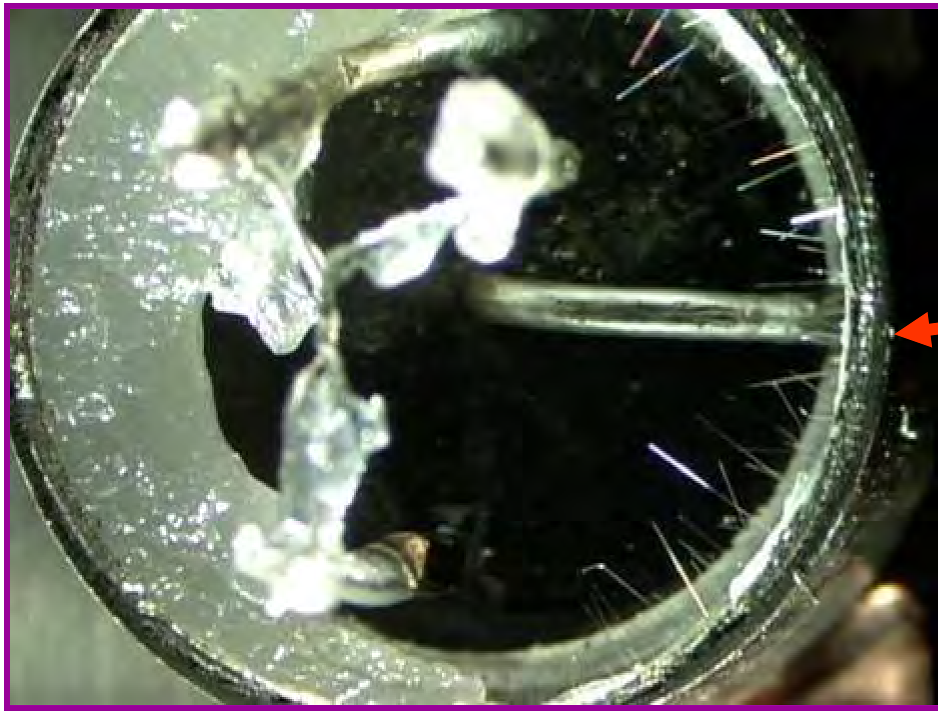


A few observations:

- **Abrupt transition ~2.6V**
  - **Larger sample size might better define distribution < 2.6V**
- **Median V_{BD} = 4.9V**
- **Accumulation of insulating films on these samples may be extensive due to age of specimens (19 years)**

Analysis of Data from PhD Dissertation of
Courey, K., "An Investigation of the Electrical Short Circuit Characteristics of Tin Whiskers", 2008-03-04
http://etd.library.miami.edu/theses/available/etd-03082008-125933/

Guess What’s Lurking Inside?



Transistor Package is Tin-Plated <u>Inside</u>.

Many Radio Malfunctions Have Been Attributed to Whiskers Shorting Case to Terminals

1960’s Vintage Transistor

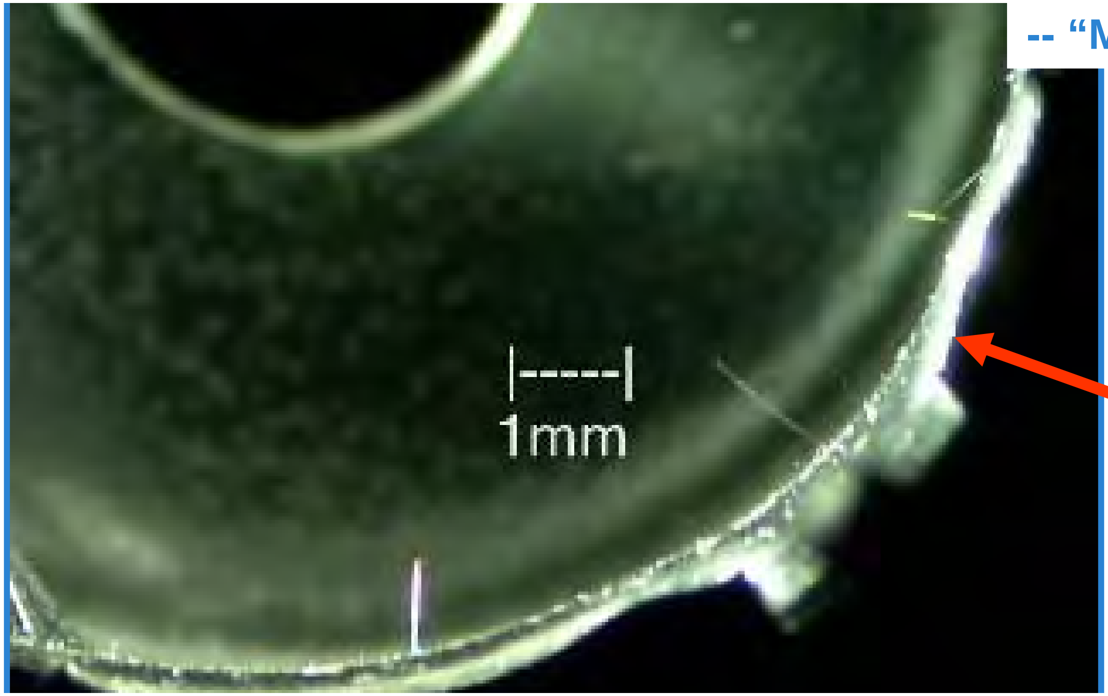
http://www.vintage-radio.net/forum/showthread.php?t=5058

Examples of Metal Whiskers

Tin-Plated Transformer Can

"We appreciate your loyalty for so many years and your email concerning the whisker growth (in our products). The push to be RoHS compliant has caused us to switch our plating process and introduce new materials that are environmentally friendly but they in turn created other problems."

-- "Manager of xxx" (July 2006)



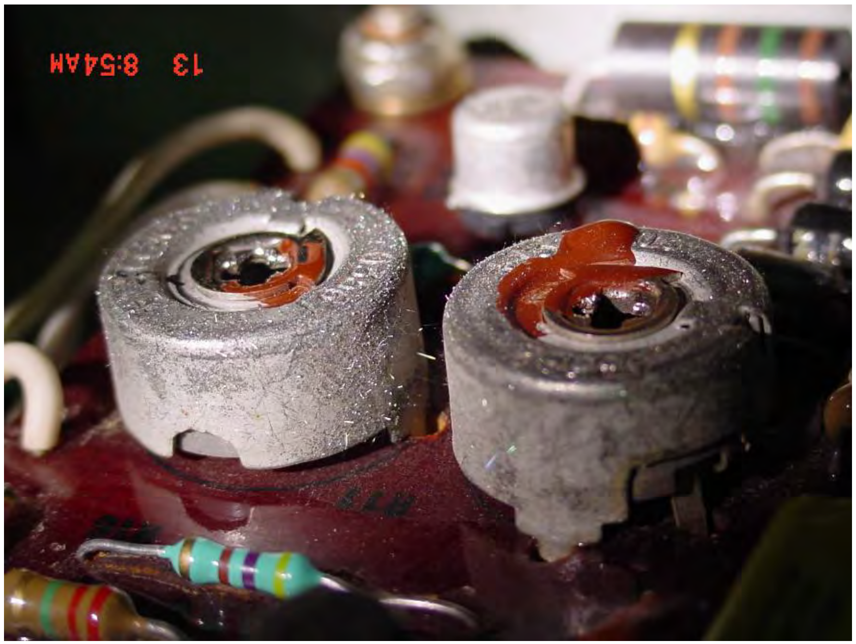
Tin whiskers observed in "as-received" cans
Coincidental with Mfr Switch from Tin-Lead to Pure Tin Finish

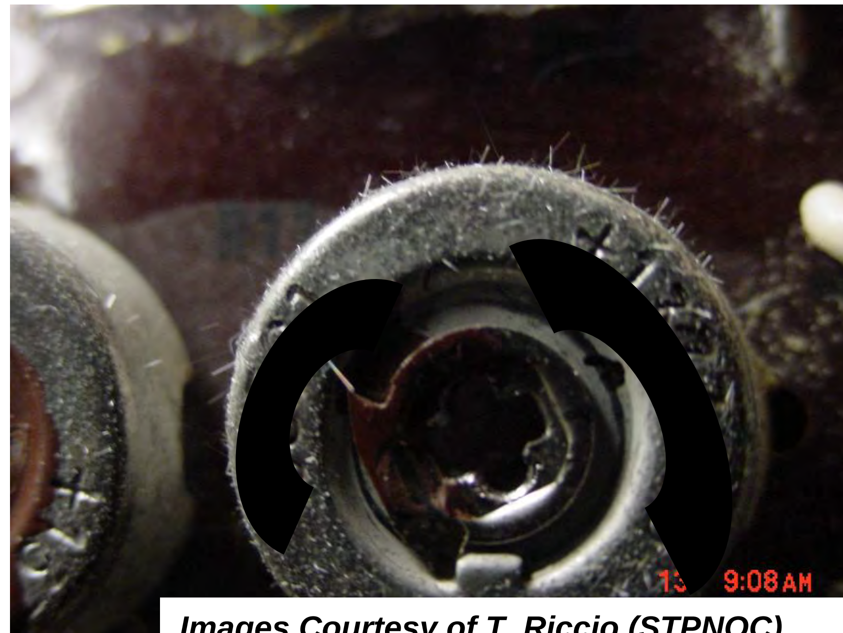
Why Are Tin, Zinc, Cadmium Still Used?

- Not all Tin (or Zinc or Cadmium) surfaces grow whiskers!
  - Rough estimate: 3% to 30% do whisker.
- Not all metal whiskers cause shorts
  - Application matters: geometry, electrical potentials, circuit sensitivity to shorting
  - Rough estimate: 3% to 30% do short.
- Not all whisker-induced shorts are traced to whiskers
  - They are very hard to see and failure analysis techniques often destroy evidence
  - Rough estimate: 0% to 10% are correctly traced.
- Not all identified whisker adventures are reported
  - Rough estimate: 0% to 3% are reported, once identified
- Hence, we expect between 0.00% and 0.03% of shorting problems caused by these coatings to be reported
  - While some 0.1% to 10% of these coatings are actually causing shorts.
  - With such a few public cases, many say “What, me worry?”
- Whiskering is dramatically inhibited when 0.5% (or more) lead (Pb) is added to Tin coatings: the shorting rate then approaches zero
  - This has been the case for the Hi-Rel community
  - But Pb use is being restricted by international legislation, and so the shorting rate may jump to 10% from zero **==> SWATCH GROUP <==**

Another Case for Whisker Mitigation Strategies?

Metal Whiskers on External Case of Potentiometers



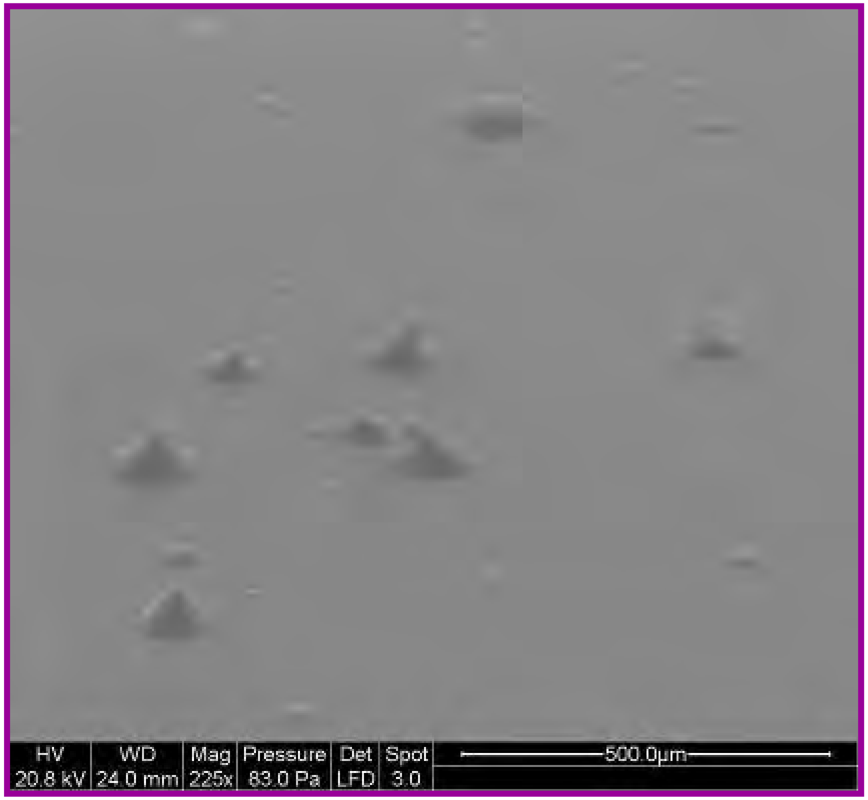


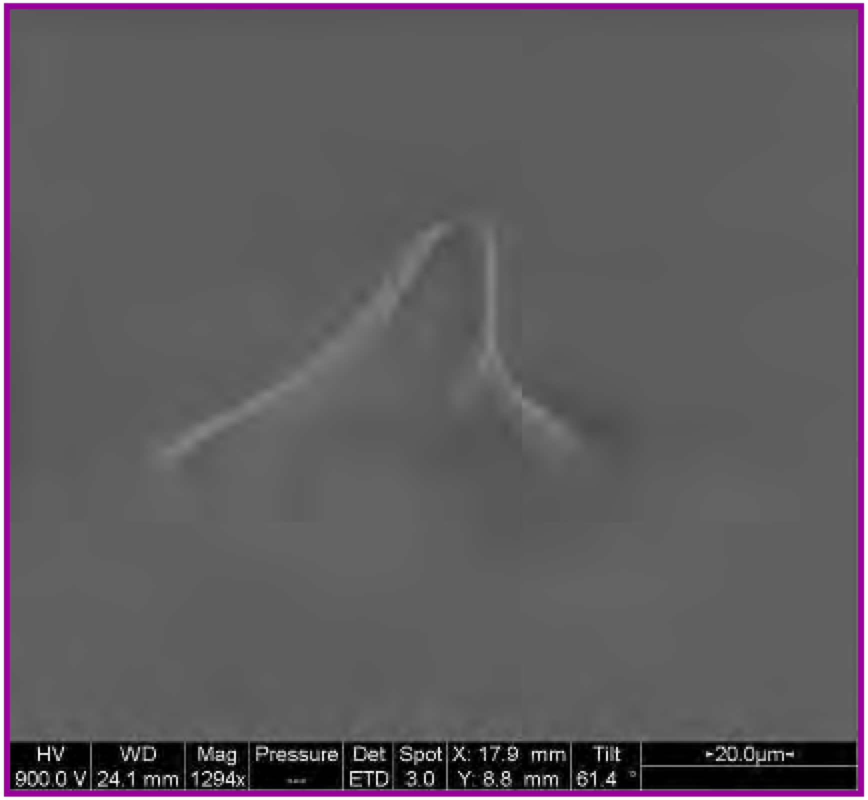
Images Courtesy of T. Riccio (STPNOC)

- No electrically insulating materials were used on the metal cases
- Metal whiskers bridging between the cases or from case to adjacent components can cause circuit malfunction

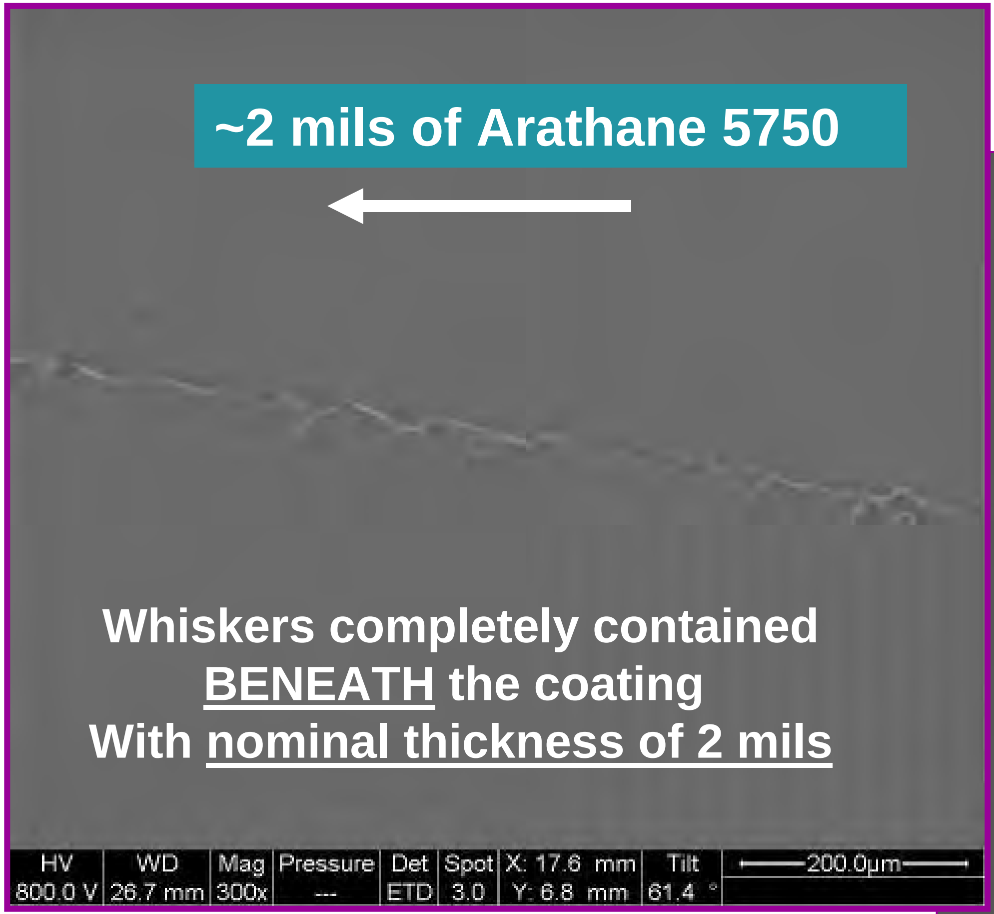
Tin Whiskers Forming "Circus Tents" in Thin Arathane 5750 Conformal Coat - 9-Years of Office Ambient Storage

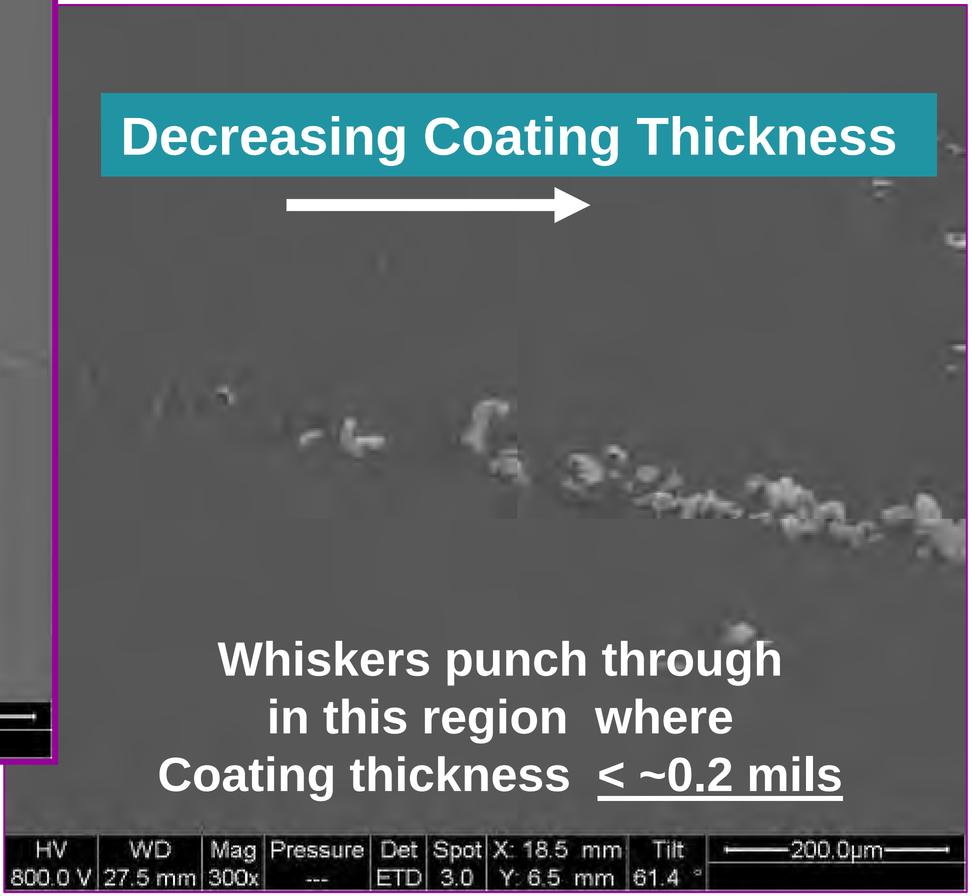
Coating Thickness < 0.5 Mil



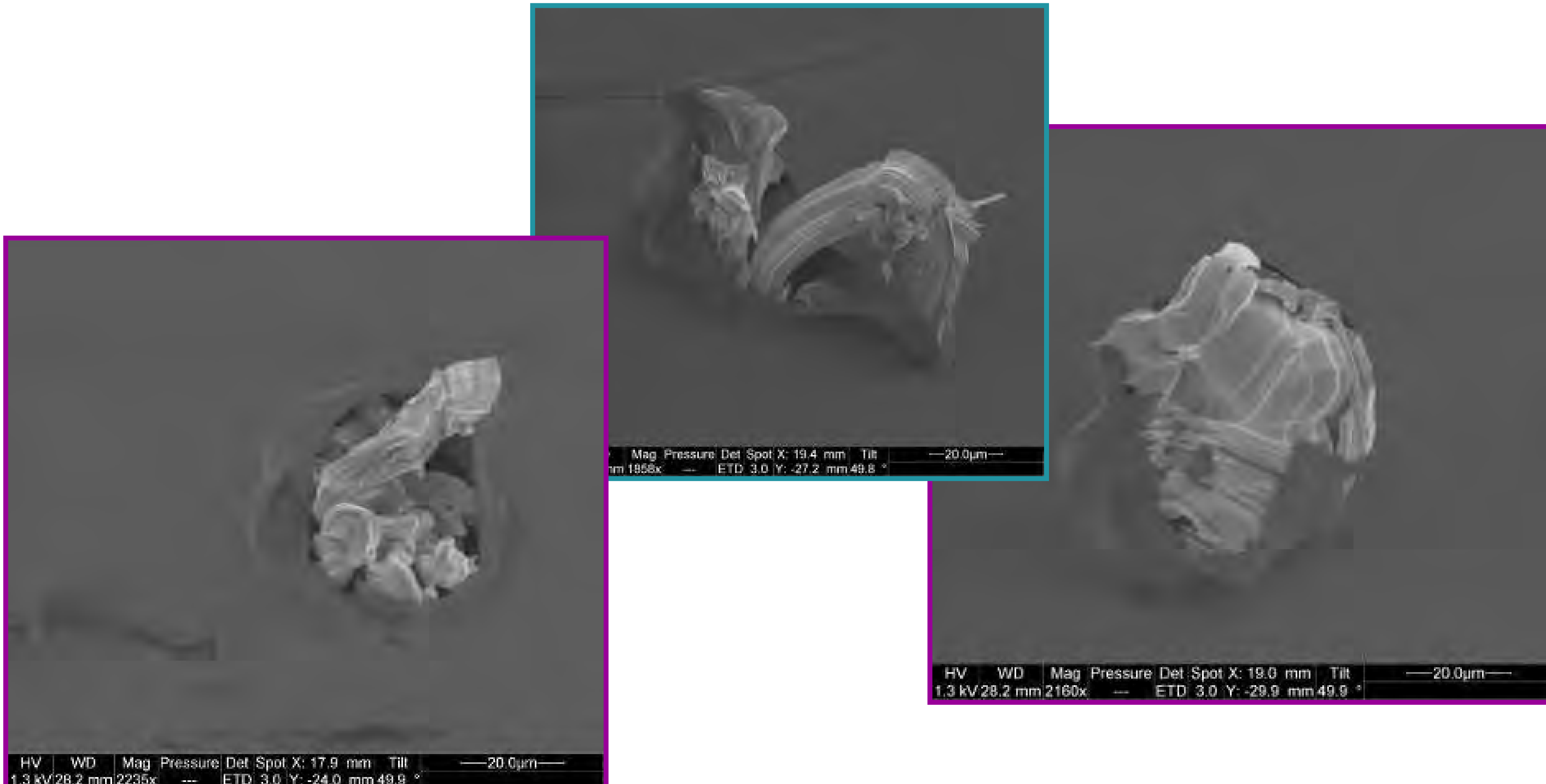


NASA Goddard Whisker Mitigation Study
Whisker Puncture vs. Coating Thickness





Tin Whiskers Rupturing THIN Coating
~0.1 to 0.2 Mils Arathane 5750 Conformal Coat
9-Years of Office Ambient Storage

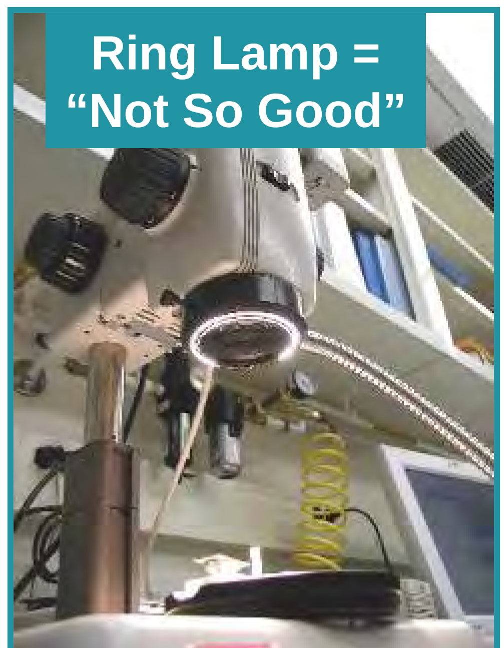


Thank Goodness for Euler Buckling and Conformal Coat on this PWB!!!

Photo Credit: M&P Failure Analysis Laboratory
The Boeing Company Logistics Depot

Optical Inspection for Metal Whiskers

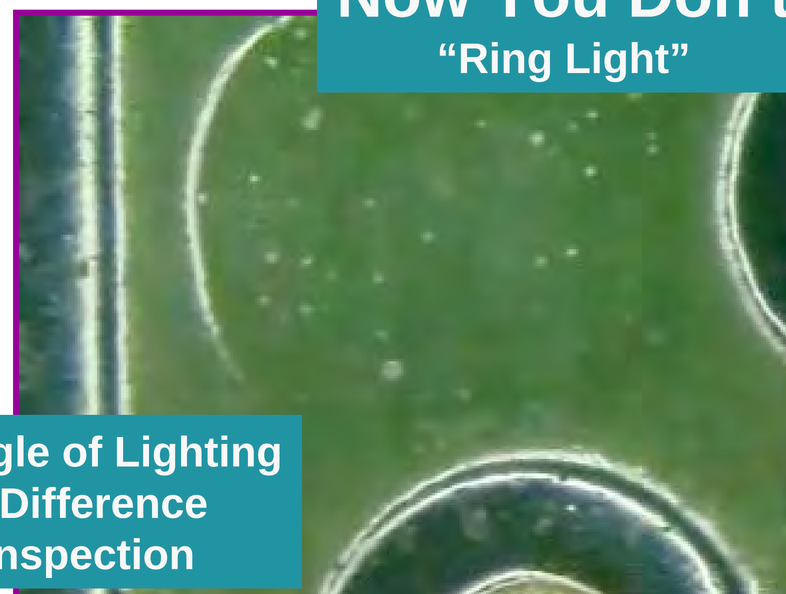
- Basic Equipment:
  - Binocular Microscope
  - Light Source: Flex Lighting PREFERRED over Ring Lamp
- Freedom to tilt sample and/or lighting to illuminate whisker facets is VERY IMPORTANT



Field Technicians and Failure Analysts Need To Be Acquainted with Metal Whiskers!!!

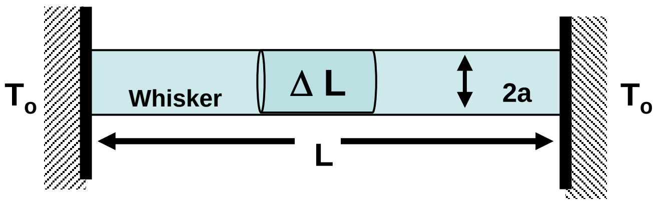
NASA GSFC has published videos to aid in optical inspection for metal whiskers

http://nepp.nasa.gov/whisker/video



Small Change in Angle of Lighting Makes Dramatic Difference During Optical Inspection

Derivation of Melting Current of a Metal Whisker in Vacuum



Assume both ends of Whisker are thermally grounded to T_o

$$\frac{du}{dt} + \Phi = source$$

du/dt **+** ***Φ*** **=** ***source***

$$u = C \cdot T \qquad c = \frac{C}{V}$$

$$u = \left(\frac{C}{V}\right) \cdot V \cdot T = c \cdot V \cdot T$$

$$u = c \cdot \Delta L \cdot A \cdot T$$

$$\boxed{\frac{du}{dt} = c \cdot \Delta L \cdot A \cdot \frac{\partial T}{\partial t}}$$

$$\Phi = \left(\frac{\partial J}{\partial x}\right) \cdot \Delta L \cdot A$$

Convection loss = 0 for vacuum
Neglect radiation loss

$$J = -k_T \cdot \frac{\partial T}{\partial x} \qquad \frac{\partial J}{\partial x} = -k_T \cdot \frac{\partial^2 T}{\partial x^2}$$

$$\Phi = -k_T \cdot \left(\frac{\partial^2 T}{\partial x^2}\right) \cdot \Delta L \cdot A \qquad k_T = \frac{L_Z \cdot T}{\rho}$$

$$\boxed{\Phi = -\frac{L_z T}{\rho}\left(\frac{\partial^2 T}{\partial x^2}\right) \cdot \Delta L \cdot A}$$

$$source = I^2 \cdot R$$

$$I = J_e \cdot A \qquad R = \frac{\rho \cdot \Delta L}{A}$$

$$source = \left(J_e^2 \cdot A^2\right) \cdot \left(\frac{\rho \cdot \Delta L}{A}\right)$$

$$\boxed{source = \left(J_e^2 \cdot A\right) \cdot \rho \cdot \Delta L}$$

$$\left[c \cdot \Delta L \cdot A \cdot \frac{\partial T}{\partial t}\right] - \left[\frac{L_z \cdot T}{\rho}\left(\frac{\partial^2 T}{\partial x^2}\right) \cdot \Delta L \cdot A\right] = J^2 \cdot \rho \cdot \Delta L \cdot A$$

$$\left[c \cdot \frac{\partial T}{\partial t}\right] - \left[\frac{Lz \cdot T}{\rho}\left(\frac{\partial^2 T}{\partial x^2}\right)\right] = J^2 \cdot \rho$$

$$I_{melt,vac} = \left[\frac{2\sqrt{L_Z T_0}}{R_0}\right] \cos^{-1}\left(\frac{T_{amb}}{T_{melt}}\right)$$